

HEAT PUMPS AS A KEY DRIVER OF A LOW-CARBON FUTURE. PART 1. HISTORICAL EVOLUTION AND DEVELOPMENT PROSPECTS IN UZBEKISTAN

Nilufar Avezova^{1*}, G'ulomjon Uzoqov², Akmal Kuchkarov¹, Abdukarimov Bekzod¹, Xalikov Abdumalik¹, Oshepkova Elvira¹, Shermatova Malika¹, Kholmatov Erkin¹, Ergashev Asror¹

¹Fergana State Technical University

²Karshi State Technical University

e-mail: avezovanr@gmail.com

Abstract

This paper presents a scientific and analytical review of the evolution of heat pump (HP) technology as a key solution for energy-efficient, low-carbon heat supply. The prerequisites and main stages of heat pump development are examined, along with the drivers of their current rapid deployment, including decarbonization, electrification of heating, and market growth. A generalized periodization of research and practical implementation (pre-1990s; 1990–2010; 2010–2024) is applied, reflecting changes in scientific priorities and deployment scales. Heat pumps are classified according to their operating principle and the type of low-temperature heat source (air, ground, water, etc.), and the main application areas are systematized: residential and public buildings, industry and energy systems, and agriculture. Key scientific and technological achievements are summarized, including more than a twofold increase in the coefficient of performance (COP), advances in compressor and heat-exchanger technologies, the transition to natural and low-GWP refrigerants, and progress in automation and exergoeconomic analysis. Particular attention is paid to Uzbekistan, where barriers to large-scale HP deployment are analyzed and promising development pathways are proposed, such as hybrid “HP + gas boiler” systems, solar-assisted heat pump complexes, geothermal installations, and low-grade heat recovery projects. The generalizations obtained in this study can be used as a scientific and analytical basis for the strategic planning of the development of heat pump technologies in Uzbekistan.

Keywords: Heat pump, decarbonization of heat supply, COP (coefficient of performance), exergy analysis, exergoeconomics, natural refrigerants, hybrid heating systems, solar-assisted heat pump systems, geothermal heat pumps, low-grade heat recovery, smart control, Uzbekistan.

1. Introduction

A heat pump (HP) is a device that transfers heat from a low-grade source to a consumer, thereby saving primary energy and reducing emissions. The idea of using a refrigeration cycle for heating first appeared in the 19th century, but HPs became widespread much later [1, 2]. Today, heat pumps are considered a key solution for decarbonizing heat supply in many analytical and policy documents, primarily in the buildings sector. According to the World Energy Committee's forecast, by 2020, up to 70% of domestic and industrial heating in developed countries should be provided by HPs. Although actual figures are somewhat lower, the rate of HP adoption is growing rapidly-according to the IEA, HPs already account for

approximately 10% of building heating needs worldwide (serving approximately 100 million households). In 2022, global sales of heat pumps grew by 11% (49% in Europe), surpassing gas boiler sales for the first time in France, while in the US, the number of heat pumps sold exceeded gas furnace sales [3]. These trends reflect the shift to electric heating as a key area for energy conservation and climate change mitigation.

Uzbekistan, which has significant natural gas reserves, traditionally covers the lion's share of its heating needs by burning gas in household and municipal boilers. However, in modern conditions, the tasks of electrifying heating and improving the energy efficiency of buildings are becoming urgent. Efficient electric heat pumps are considered a promising

Received: 20 May 2026

Revised: 07 July 2026

Accepted: 15 September 2026

<https://doi.org/10.67846/jcet.2026.42113>

alternative to gas boilers for reducing CO₂ emissions and saving fuel [4]. Pilot projects for the use of heat pumps are already underway in the country. For example, in 2023-2024, with the support of the GEF, a heating system for a rural school was tested using a combined use of heat pumps and a solar photovoltaic station instead of a coal-fired boiler [5]. The results of the analysis showed an acceptable payback period for the investment and significant environmental benefits of such a system. Nevertheless, for the widespread implementation of heat pumps in Uzbekistan, it is necessary to take into account climatic conditions (hot summers and cold winters), the structure of energy consumption (the predominance of cheap gas), and economic realities (high initial cost of equipment).

This paper presents a fundamental overview of the development of heat pump technology-from its origins in the early 20th century to the present-classifying the main stages of research. It examines the potential and areas of practical application of heat pumps (industry, housing and utilities, agriculture, energy, etc.), key scientific achievements (theory, design, efficiency, exergoeconomics, automation, etc.), current challenges (globally and for Uzbekistan), and the most promising areas of research and implementation of heat pumps in Uzbekistan. The review draws on both domestic literature and contemporary international research to provide a scientific and analytical foundation for determining priorities for the development and implementation of heat pumps in Uzbekistan.

Historical Stages of Heat Pump Research. The history of heat pumps spans over 150 years, but interest in their research and implementation only significantly increased in the second half of the 20th century. This evolution can be roughly divided into three stages: the early period (before the 1990s) -the inception of ideas and initial implementations; the period 1990-2010 -growing interest, technological improvements, and the beginning of widespread use; and the current stage (2010-2024) -a sharp increase in the adoption of heat pumps, as evidenced by sales statistics and expanding applications. Below is an overview of these stages, with the rationale for defining their boundaries.

Early period (before 1990s). Although the operating principles of the HP are based on the classical principles of 19th-century thermodynamics (the idea of using a working fluid to transfer heat from a cold to a hot reservoir was proposed by W. Thomson (Lord Kelvin) as early as 1852), practical implementations appeared later [1]. The Austrian engineer Peter von Rittinger built the first experimental HP installation in 1855-1857 -a vapor compression system for evaporating salt brine at a

saltworks in Ebensee (Austria) [6]. This installation had a capacity of approximately 14 kW and demonstrated fuel savings of up to 80% compared to direct heating with wood, although due to technical difficulties of the time it was of an experimental nature. The further development of refrigeration machines in the second half of the 19th and early 20th centuries (the work of K. Linde, the development of compressors and refrigerants) paved the way for the emergence of heat pumps, but until the 1920s and 1930s, they remained an engineering rarity. In 1912, Swiss engineer Heinrich Zölli patented an electric ground source heat pump for heating (Swiss Patent No. 59350), but at the time, this idea was ahead of the technological level [6].

The first large-scale examples of using heat pumps for heating were installations in the 1930s and 1940s. In Zurich (Switzerland) in 1937-1938, the Escher Wyss company designed and implemented a heat pump system (using R-12 refrigerant) for heating the city municipality (Rathaus) with a capacity of ~100 kW [6]. This heat pump used the energy of the Limmat River water and, during the first heating season of 1938-1939, demonstrated an average seasonal conversion factor of approximately 2.16, taking into account all auxiliary costs. The installation operated without interruption for 63 years (with periodic modernization) and was only replaced with a modern unit in 2001. In Great Britain in 1945, engineer John Sumner in Norwich developed the first large-scale heat pump system for heating a building, using water as a heat source [2]. Although it demonstrated high efficiency, widespread adoption was hampered by low prices for traditional energy resources (coal) in the post-war period. Around the same time, in 1948, one of the first geothermal heat pump heating and cooling systems was installed in the Equitable Building (Portland, Oregon) in the United States; this installation was subsequently designated a historic engineering landmark [2].

In the 1960s-1980s, research and application of heat pumps intensified under the influence of the energy crisis. The oil shocks of 1973 and 1979 led to increased interest in energy-saving technologies, especially in countries with cold climates. For example, in Sweden and Switzerland, by the end of the 1980s, heat pump systems had already begun to significantly penetrate into the heating of private homes [2, 6]. In the USSR, research was also undertaken, and schemes for the application of heat pumps in heating systems and technological processes were developed. Thus, the dissertation of G.B. Garoyan (1965) was devoted to the issues of the efficient application of heat pumps in radiant panel heating, taking into account the climate. In the 1970s, articles were published on the integration of heat pumps into chemical-engineering processes and the storage of agricultural products. Nevertheless,

until the 1990s, the use of heat pumps in practice remained isolated. According to review papers, in the 1970s, no more than a few publications on HPs were published annually, but by the late 1980s, their number had grown to dozens. For example, in 1988, 13 publications on the topic were noted in domestic journals, demonstrating a surge in scientific interest at the end of the Soviet era. The main achievements of the early period were the formation of a theoretical framework (generalization of the Carnot cycle for HPs, assessment of marginal COPs), the accumulation of operating experience from the first units, and the recognition of their potential role in energy conservation.

Development in the 1990s-2010s. The early 1990s marked a new stage in the history of heat pumps. A sharp increase in attention to environmental issues (the 1987 Montreal Protocol on ozone-depleting refrigerants, the 1997 Kyoto Protocol on greenhouse gas reduction) stimulated the development of more advanced and environmentally friendly heat pump technologies. At the same time, technological progress was taking place in refrigeration equipment itself: inverter compressors and control electronics in the 1990s made it possible to significantly increase the energy efficiency of heat pumps by adapting performance to the load. For example, in the United States, it was only by the 1990s that the energy efficiency movement gained momentum -the minimum standard values of seasonal energy efficiency ratio (SEER) for air conditioning equipment were raised to 10, which prompted manufacturers to improve heat pump units [2].

Heat pumps also saw development in Europe and Asia during this period. Japan and the EU countries actively implemented heat pumps in building heating, seeking to reduce fuel imports. Advances in refrigerant replacement played a major role: ozone-safe HFCs (R134a, R410A, etc.) began to be used instead of phased-out CFC freons, and interest in natural refrigerants -ammonia, carbon dioxide, and propane -also revived [6]. The advent of the CO₂ heat pump was an innovative breakthrough: a Japanese program to develop a domestic heat pump for water heating culminated in 2001 with the release of the EcoCute system, the first commercial domestic CO₂ heat pump [7]. This technology made it possible to produce water at temperatures up to 90°C with a high COP and minimal impact on the climate (CO₂ as a refrigerant does not destroy ozone and has a low global warming potential). By 2015, total sales of EcoCute in Japan exceeded 4.6 million units, demonstrating the commercial success of the innovation.

In cold climate countries (Northern Europe, Canada), solutions for efficient operation of heat

pumps at low air temperatures were developed in the 1990s and 2000s-for example, two-stage cycles, intermediate heat exchangers, and steam injection. This made it possible to overcome the previously inherent drawback of air-heating pumps: power loss in extreme cold. By the late 2000s, heat pumps had confidently conquered the heating sector of new buildings in many developed countries. The experience of Switzerland is indicative: despite the presence of a well-developed gas distribution network, approximately 75% of new detached houses in Switzerland in the early 2010s were heated by heat pumps [6]. By 2010, several million heat pumps of various types had been installed across Europe as a whole, with adoption rates growing at 10-20% annually.

2. Materials and Methods

One criterion by which to judge the growing interest in heat pumps in the scientific community is the number of publications. In the Russian-language literature of the 1990s, an average of 5-15 papers were published per year, whereas in the 2000s, this number increased significantly, reaching a peak in 2010-2011. Figure 1 shows the dynamics of publication activity on heat pumps in Russia/CIS from 1970 to 2020. A clear acceleration is evident after 2000, which coincides with the development stage described.

The rationale for marking the end of the second stage by 2010 is that by this time, heat pumps had ceased to be a niche device and had become a mass-market technology for heating and hot water supply in developed economies. Further growth required addressing new challenges-integrating heat pumps into energy systems, working with renewable energy, and so on-which characterize the next stage.

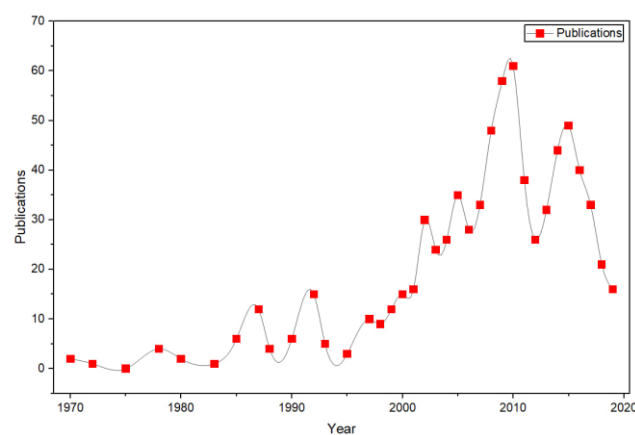


Fig.1. Dynamics of the number of publications on heat pumps (1970-2020) according to a bibliographic review. A sharp increase in interest in the topic was observed after 2000, reaching a peak in 2010-2011 (CIS countries).

The current stage (2010-2024). The period since 2010 has been marked by the transformation of heat pumps into one of the central elements of the sustainable energy development strategy. The impetus was provided by global efforts to reduce greenhouse gas emissions (the 2015 Paris Agreement, etc.), as well as the technological maturity of heat pump solutions. Over the past decade, there has been a high growth rate of heat pump sales worldwide -by an average of 10-15% per year, with acceleration in 2021-2023 [3]. The European market is particularly dynamic: a record growth of 40-50% in 2022 was driven by both environmental goals and the energy crisis (the search for alternatives to gas). A number of countries have introduced bans on the installation of new gas boilers in the future (France, the Netherlands, etc.), which guarantees a further increase in the share of heat pumps in the heating sector. In 2022 Heat pump sales in France have surpassed those of gas appliances, and a similar trend has emerged in the United States.

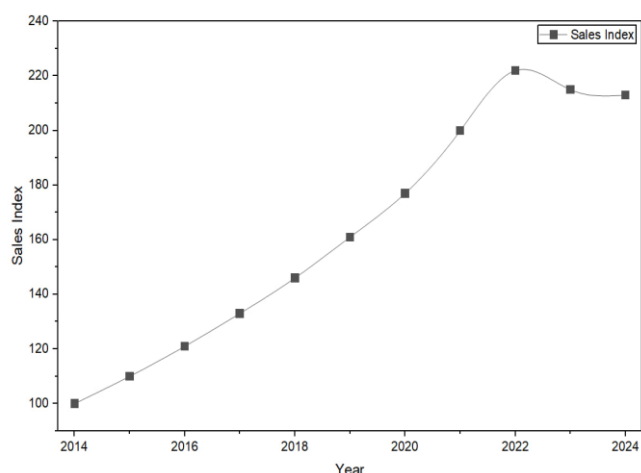


Fig. 2. Global heat pump sales growth (index, 2014 = 100): 2014-2020 - average growth rate of about 10% per year; 2021 -+13% compared to 2020; 2022 -+11% compared to 2021. Note: in 2020, there was a temporary decline in sales (~-3%) due to the pandemic; the graph reflects a smoothed trend.

Source: EHPA "Heat Pumps in Europe. Key Facts & Figures" (IEA data recalculated) and IEA commentary on sales growth in 2022.[8]

From a scientific and technical perspective, the current stage is characterized by several trends. A new niche is emerging: heat pumps for high-temperature heat (100-150°C) and for industrial applications. Large energy companies and manufacturers have begun producing large-capacity heat pump units (with a capacity of tens of MW) for heating urban district heating networks and utilizing industrial waste heat. The IEA notes that industrial and district heat pumps play a critical role in the decarbonization of heat supply and require special attention from science and industry [3]. Refrigerants continue to improve: stricter

regulations on HFC gas (Kigali Agreement 2016) have stimulated research and implementation of low-GWP working fluids - ammonia, CO₂, hydrocarbons, as well as new low-GWP synthetic blends. The current trend - a return to natural refrigerants - is even reflected in the titles of case studies, such as "Natural Refrigerants in Heat Pumps: Pushing the Boundaries of Sustainability" (HPT Magazine, 2025) [7]. In the age of digitalization, the importance of intelligent heat pump management is growing: systems for remote monitoring, self-diagnostics, tariff optimization, and integration with smart grids are being implemented. Heat pumps are becoming part of the Smart Grid and Smart Home concepts, which requires research in automation and communications. In recent years, the focus has shifted to scaling up production and reducing the cost of heat pumps (see Fig. 3).

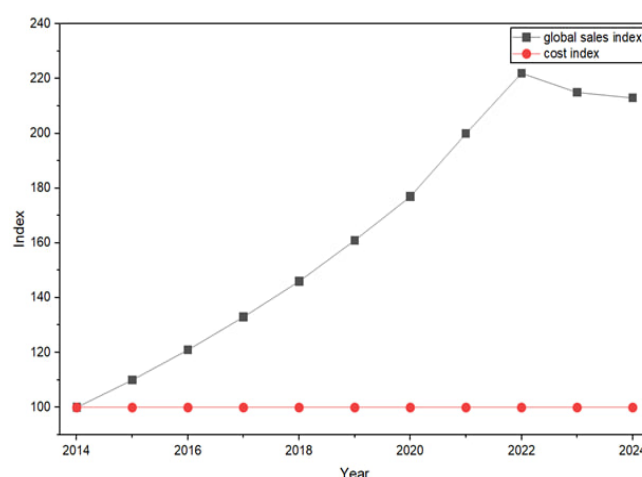


Fig. 3. Market scaling and price dynamics of heat pumps (index, 2014 = 100).

An analysis of the data presented in Fig. 3 shows that the "Sales" line is an estimate of the dynamics of global sales of HT as a proxy for the scaling of their production; the average growth is ~10%/year in 2014–2020 to ~8 million units, then +13% (2021), +11% (2022), and -3% (2023). The "Cost" line is a qualitative recording of the JRC conclusion that the cost of HT in the EU has remained "roughly constant" over the past 10 years with an increase in efficiency. [8-10]

The world's largest manufacturers (more than 40% of TN are produced in China) are increasing production, but to meet demand, stable supply chains for key components (compressors, electronics) are needed [3]. (See Fig.4)

Despite the more than doubling of the heat pump market over the past decade (scaling up production and sales), there has been no reduction in cost for the end consumer. Sweden, for example, shows that the nominal cost of installations has increased significantly (+40% from 2015 to 2024), while in real terms (adjusted

for inflation), it remains approximately at the 2015 level or slightly higher. Consequently, the current research focus is naturally shifting to cost reduction: reducing the cost of equipment and, especially, installation/infrastructure (standardization of solutions, localization of components, increased installation productivity, optimization of supply chains).

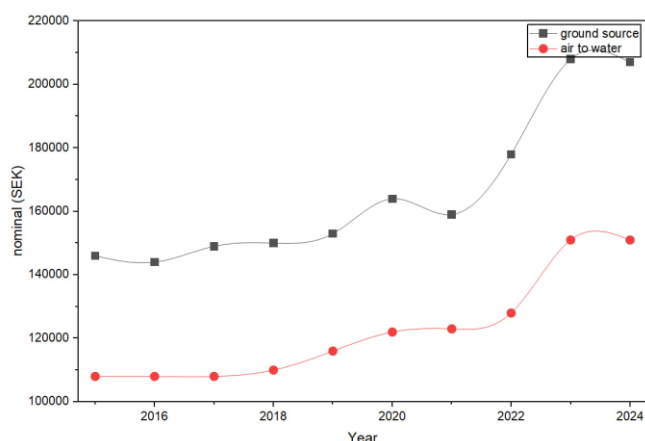


Fig. 4 Sweden: Heat pump installation costs (nominal), 2015-2024.

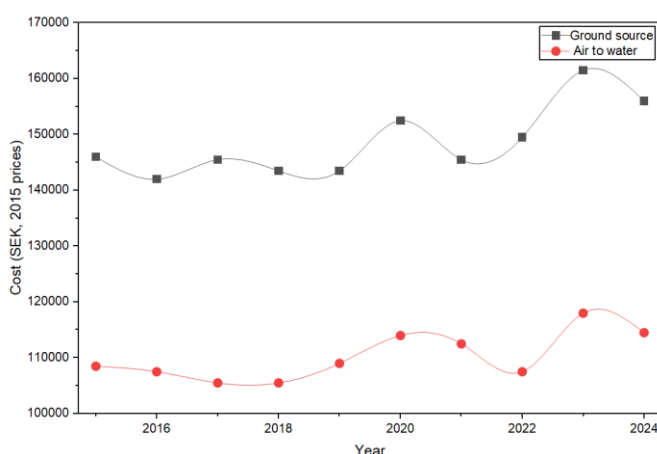


Fig. 5 Sweden: Heat pump installation costs in 2015 prices (CPI deflated), 2015-2024.

Figure 4 shows the estimated total cost (equipment + installation) for a typical project: Bergvärme (ground/borehole heat pump) and Luft/Vatten (air-water). Figure 5 shows the nominal values from the SKVP 'Pulsen 2024' converted to 2015 prices using the CPI (annual average index) [11].

For Uzbekistan, the current stage represents the beginning of active interest in heat pumps. While before 2020, the implementation of heat pumps was sporadic, in recent years a number of initiatives have been developing in the country.



Fig. 6 a) Demonstration energy-saving residential building of the "Near Zero Energy" type (Yoshlik mahalla, Nurafshan city, Tashkent region): a 16 kW solar power plant and solar collectors for hot water supply are located on the roof; heating/cooling is implemented using a heat pump.



Fig. 6 b) School No. 19 (mahalla "Iftikhor", Bayavut, Syrdarya region): heating on heat pumps, 3×HP, total 340 kW

Figure 6a) shows a photo of a "Near Zero Energy" residential building (Yoshlik mahalla, Nurafshan). It is equipped with a combination of renewable energy sources and energy-efficient engineering solutions: a 16 kW photovoltaic system is installed on the roof, along with solar collectors for hot water supply. A heat pump is used for heating and cooling. Electricity from the photovoltaic system is used for the building's own needs, and any deficits or surpluses are balanced through the grid. High thermal insulation of the building envelope, increased air tightness, proper orientation, and shading elements reduce heat loss and the load on the heating system, ensuring the building achieves near-zero energy consumption. Figure 6b)

shows the building of comprehensive school No. 19 in the Iftikhor mahalla (Bayavut district, Syrdarya region, Uzbekistan), where a heating system based on heat pumps has been implemented: three units with a total installed capacity of 340 kW, which are classified as low-temperature heat sources (up to ~55 °C) and are used for space heating/cooling (including through fan coil units), with a typical energy conversion efficiency of approximately 1:3.8 (air-to-water) to 1:5 (water-to-water). It should be noted that the transition from coal to heat pumps resulted in a reduction in emissions of approximately 446 tons of CO₂-eq/year (compared to the coal option to achieve the required temperature regime).

Research in Uzbekistan is underway on heat pump technologies applicable to local conditions, including analyses of the efficiency of heat pumps in cottage heating systems, exergy analysis of a solar heat pump dryer for agriculture, and the use of heat pumps to recover heat from recycled water at enterprises. State policy is also beginning to take into account the potential of heat pumps, and issues of electrifying heating systems and phasing out coal and inefficient boilers are being discussed in the context of energy conservation programs. Thus, for Uzbekistan, the current stage can be considered a starting point for the widespread adoption of heat pump technologies, which underscores the relevance of assessing their development prospects in the country [12].

Classification and application of heat pumps. Heat pumps are classified by various criteria, including operating principle, type of low-potential heat source, intended use, and more. Below are the main categories of heat pumps and their practical applications (with typical examples). Table 1 summarizes the classification by type and source.

Types of TN by operating principle:

1. Vapor-compression (mechanical) heat pumps are the most common type, where the working fluid (refrigerant) sequentially evaporates at a low temperature, is compressed by the compressor, and condenses at a high temperature, releasing heat. Energy to drive the compressor can come from an electric motor or an internal combustion engine. Modern electric compression heat pumps provide a performance coefficient (COP) of 3-5 or higher (depending on the operating mode) and are used in all scales -from domestic (several kW) to large industrial (megawatts). For example, air and geothermal heat pumps for heating buildings fall into this category. In the Russian literature, vapor-compression heat pumps have been extensively studied since the 1970s, including from an exergy perspective, and a generalization of the theory of such machines is presented in fundamental works [13].

2. Absorption heat pumps are devices where the compressor cycle is replaced by a thermochemical one: in the generator, the liquid absorber is heated by external heat (e.g., gas combustion) and desorbs the dissolved refrigerant, which then condenses, giving off useful heat, and is absorbed back. A typical example is water-ammonia or lithium bromide absorption refrigeration machines, operating as heat pumps when utilizing low-grade heat. The COP of absorption HPs is usually lower (1.2-1.8), but they allow the use of thermal energy instead of electricity. In the 2000s, special publications were published devoted to the new generation of absorption heat transformers, reflecting the maturity of this technology. In Russia and the CIS, absorption HPs are used primarily in large systems (e.g., for utilizing the heat of flue gases or industrial waste heat) [13].

Adsorption (solid-absorption) heat pumps are a type in which refrigerant vapor is periodically absorbed by a solid porous material (zeolite, silica gel, etc.). These intermittently operating units are in demand where free heat is available (solar collectors, waste heat). Their advantages include simplicity, the absence of moving parts, and a relatively low average coefficient of performance (COP) (~1.1-1.3). Adsorption heat pumps are in the experimental development stage and are in niche applications (e.g., for autonomous solar refrigerators) [13].

3. Results

Heat pumps using other principles include thermoelectric (Peltier) pumps, thermoacoustic pumps, magnetocaloric pumps, and others. A thermoelectric heat pump is a semiconductor module that transfers heat when current is passed through it; it is compact and reliable, but has a very low efficiency (COP of about 1), so it is used primarily for small cooling devices (e.g., car refrigerators). Magnetic and acoustic heat pumps are in the laboratory research stage and do not compete with compression pumps in terms of prevalence in the foreseeable future [13].

Classification by low-potential heat source: Air source heat pumps (air-to-air, air-to-water) - extract heat from the outside air. These are the simplest and most widely used systems (a typical household air conditioner is essentially an air-to-air heat pump capable of operating in heating mode). The advantage is that they do not require drilling or heat exchangers; an outdoor unit is sufficient; the disadvantage is a decrease in power and COP in freezing temperatures. They are effective in moderate and warm climates; for cold winters, they are often used in combination with a backup heater. Nevertheless, the latest models with an inverter drive and a two-stage cycle are capable of

operating efficiently even at -20 °C outside air, providing a COP of ~2.5-3.0 [2]. In Russia/CIS, research into air source heat pumps is actively underway, for example, analyzing their efficiency in different climatic conditions and optimizing the operating modes of ventilation heat pumps.

Geothermal (ground) heat pumps extract heat from the ground or groundwater. They have a more stable and higher COP during the heating season (~4-5), as the ground temperature in winter is significantly higher than the air temperature. They are classified as systems with a horizontal collector (pipes buried in the ground) or with vertical wells, as well as groundwater (open-loop) systems. Geothermal heat pumps are widely used in Europe, the USA, and China for heating buildings, especially where a high efficiency is required. There is also interest in them in the CIS: projects for decentralized heating of villages based on geothermal heat pumps have been described, as well as experience with implementing geothermal heat pumps for heating in cold climates (Siberia). For Uzbekistan, with its continental climate, geothermal heat pumps are particularly attractive - in winter, the ground is much warmer than the air, and in summer, it is cooler, resulting in efficiency gains for both heating and air conditioning [13].

Water-source heat pumps (WHRPs) utilize natural bodies of water (rivers, lakes), groundwater, or industrial wastewater as heat sources. Water temperatures in winter are typically above 0°C, ensuring a COP between air- and ground-source

systems. Examples include heat pump stations that utilize the heat of recycled cooling water from thermal power plants (TPPs) or the heat of municipal wastewater. In Russia, projects have been developed for autonomous heating substations based on HPs that utilize wastewater heat (e.g., in Novosibirsk). In Uzbekistan, WHRPs could be used at facilities with high water consumption (e.g., at TPPs to heat network water using condenser heat). Domestic researchers have proposed a system for utilizing the heat of recycled water using HPs - such a setup could increase the efficiency of the energy cycle [13].

Combined (hybrid) systems - a combination of a heat pump with other sources. For example, solar heat pump systems: the solar collector heats the refrigerant or intermediate circuit, increasing the efficiency of the heat pump. In the domestic literature, combined solar heat pump units are described for heating energy-efficient houses, as well as for drying chambers in agriculture. Another option is a heat pump with ventilation heat recovery (supply and exhaust units with a heat pump) for buildings with a high demand for fresh air; they extract heat from the exhaust air and transfer it to the supply air. There are also hybrid "HP + boiler" systems, where the HP covers the base heat load, and peak heating is provided by a gas boiler. Such systems are popular, for example, in Italy (up to 40% of HP sales are hybrid systems) [3], and are of interest for Uzbekistan, where gas is still available and can be used for peak additional heating. Table 1 presents the main areas of HP application.

Table 1. Areas and fields of application of heat pumps

	TN type	Operating principle and energy source	Examples of low-grade heat sources	Application areas (examples)
	Vapor compression (electric or motor)	Compression of refrigerant vapor by a compressor (electricity or motor)	Air, soil, water, exhaust gases, process heat	Domestic and commercial heating/cooling, hot water supply; heat pumps in heating networks; ventilation heat recovery; cooling and heating of process lines.
	Absorption (thermal)	Absorber generator, absorber cycle (uses fuel/steam heat)	Flue gas heat, geothermal water, solar collector	Utilization of low-grade heat at combined heat and power plants and industrial enterprises; heating from gas boilers (increased efficiency); refrigeration units using waste heat.
	Adsorption (solid-sorption)	Vapor sorption/desorption cycle in solid porous media	Solar energy, waste heat (periodic cycle)	Solar coolers for air conditioning without electricity; experimental autonomous heating and cooling units.
	Thermoelectric	Peltier effect (direct conversion of electrical	Electricity (DC) - cold and hot junction	Small refrigerators (car, portable), electronics cooling, low-power local air conditioners.

		energy into heat transfer)		
	Combined(hybrid)	Combination of several methods or sources	Solar + air (or ground); HP + boiler; water-water + cooling	Energy-efficient buildings (solar heat pump heating and hot water supply systems); heating networks with multiple sources; systems with seasonal heat storage.

As you can see, heat pump technologies cover a wide range of applications, from domestic to industrial. Let's examine the main practical applications of heat pumps in more detail:

Industry and energy. In the industrial sector, heat pumps are used primarily to recover low-grade heat from technological processes and subsequently use it beneficially. Many industries (chemical, oil refining, food industry) produce waste heat-heated water, steam, gases-which are typically discharged into the environment. Heat pumps allow the temperature of this "waste" energy to be raised to a level suitable for technological needs. For example, in the chemical industry, systems with compensating heat pumps included in the heating-cooling cycle have been implemented: a heat pump unit extracts heat from the cooled flow and transfers it to preheat another flow, reducing steam or fuel consumption. Research [14] has demonstrated the possibility of optimizing the overall heat pump in chemical engineering processes and has also assessed the efficiency of compensating heat pumps under various operating conditions. In the USSR, as early as the 1980s, the use of steam jet heat pumps for the recovery of waste heat from chemical production-for example, the heat of reaction gases-was being considered. These ideas are currently being revived at a new technical level: there are pilot projects for heat pumps that return ~50% of the thermal energy from washing, drying, and other processes back into production, with exergy efficiency of up to 60-70%.

Heat pumps are a separate area of research in the energy sector. Here, their purpose is to increase the efficiency of electricity and heat generation. One example is the inclusion of a heat pump in the thermal power plant cycle to recover heat from the turbine condenser. In a traditional thermal power plant, a significant portion of the energy is lost with warm circulating water in the cooling tower. By directing this water through a heat pump, its temperature can be raised and used for heating (the "electricity + useful heat" scheme), turning the thermal power plant into an efficient combined heat and power plant. Soviet scientists proposed similar schemes as early as the 1970s, and today they are being revisited in the context of hybrid power plants. For example, in 2012 [15] M.A. Molodkina investigated the possibility of improving

the technical and economic performance of a combined cycle power plant by utilizing low-grade heat using a heat pump. The results showed that heating feedwater or blast air through a heat pump can improve the plant's efficiency and reduce specific fuel consumption. Another example is expander-generator units at gas distribution stations: a heat pump system can be used to heat natural gas before throttling (expansion), capturing heat from the environment instead of burning the gas in heaters. Such units were discussed in the works of V.S. Agababov et al. [16].

Heat pumps are also used in cogeneration and trigeneration units. In trigeneration systems (simultaneous production of electricity, heat, and cold), an absorption chiller using waste heat is often used for cooling. It can be considered a heat pump operating on high-temperature heat. Current research is aimed at creating vapor-compression heat pumps capable of producing temperatures of 120-150°C, in order to directly replace steam heaters in enterprises. Implementations have already been implemented. For example, since 2011, the world's largest ammonia heat pump (14 MW) has been successfully operating in Norway, heating water to 90°C for the city's district heating network [17]. In Japan, industrial CO₂ heat pumps have been installed that generate 90°C water for food production, replacing boilers and reducing CO₂ emissions by 40-50%.

A study conducted in Pisa, Italy, proposed a trigeneration microgrid that, in addition to an internal combustion engine and absorption chiller, includes a reversible heat pump to meet peak heating and cooling loads. Simulations showed that replacing a gas boiler with a heat pump reduces annual costs by approximately 7% and CO₂ emissions by 11%. As can be seen, integrating a heat pump into a cogeneration/trigeneration system ensures the simultaneous generation of electricity, heat, and cooling with maximum fuel efficiency and minimal losses.

Thus, in industry and energy, heat pumps allow low-potential heat to be put into circulation and the efficiency of energy complexes to be increased.

Housing and utilities (building heating and cooling). Heat pumps are most widely used in the heating and cooling of buildings. Their use in housing

and utilities (HUI) includes individual home heating, district heating systems, hot water preparation, air conditioning, and ventilation. The main segments are highlighted below.

Individual heat pumps for heating buildings. In private homes, cottages, and low-rise buildings, heat pumps (most often air-to-water or ground-to-water) are used to heat rooms through a system of radiators or underfloor heating, as well as to produce hot water. During warmer months, such units can operate in cooling mode (reversible models). In Europe and North America, this is a steadily growing market, with hundreds of thousands of installations per year. In colder regions, geothermal and air-to-water systems with an additional electric heater for extreme cold are preferred. In moderate climates, air-to-air heat pumps (split systems) for combined heating and air conditioning are common. The main advantages of heat pumps are 30–60% energy savings compared to electric heating and liquid fuels, a high degree of automation, and the absence of combustion products on-site. Disadvantages include high initial cost, requirements for qualified installation personnel, and reduced efficiency at low outdoor temperatures for air-to-air systems. In Uzbekistan, where residential areas traditionally rely on gas for winter heating, individual heat pumps could significantly reduce gas consumption. However, they have not yet become widespread due to subsidized gas prices and the high cost of imported equipment. Nevertheless, there are a number of examples of imported heat pumps being installed in new cottages, especially in remote areas without gasification. An economic analysis for Uzbekistan shows that, given commercial coal/diesel fuel prices, heat pumps are already competitive for heating schools and social facilities [18], especially when combined with solar panels for power supply. A key issue is reliable operation during extremely hot summers and dusty air; this requires the selection of appropriate models and regular maintenance.



Fig. 7. Individual air-to-water heat pump Viessmann, providing heating of a private house and hot water supply; Uzbekistan

Figure 7 shows a modern energy-efficient cottage equipped with a Viessmann air-to-water heat pump. The outdoor unit (on the right) extracts heat from the outside air and heats the water to $\sim 65^{\circ}\text{C}$ for the radiators and underfloor heating. This switch to electric heating eliminates the need for a gas boiler and reduces heating energy consumption by 3–4 times.

Heat pumps in district heating systems. Heat pump units can be integrated into municipal heating networks to partially or completely replace boilers. Various configurations are possible, such as a large heat pump at a central source (CHP or boiler house), which raises the temperature of the water returning to the network, improving fuel efficiency at the source; decentralized heat pumps at neighborhood or building heating stations, which extract heat from the environment or wastewater and provide additional heating for the coolant.

The use of heat pumps in heating networks is relevant in the off-season and mild winters, when the temperature of the network water can be kept low (~ 50 – 60°C) - then the COP of the heat pump is maximum. Experience of such application exists in Scandinavia, Germany, and Japan. In Russia, plans are being developed to convert a number of heating systems to a low-temperature mode with heat pumps. Large-scale district heating schemes based on heat pumps utilizing low-potential heat emissions from power plants or industrial enterprises have been studied. Ovsyannik A.V. et al. (2008) [19] proposed a concept for city heat supply using a cascade of heat pumps extracting heat from low-temperature sources (CHP waste, groundwater, etc.). In Uzbekistan, there are no implemented projects with heat pumps in the centralized heating system yet, but the use of a heat pump in urban wastewater treatment plants, for example, is of interest. Wastewater heat (typically 10 – 15°C in winter) can be converted into useful heat for a neighborhood. Pilot projects have been described in Russia where a 700 kW unit using municipal wastewater provides heat to a residential area. Compact air source heat pumps combined with existing hydronic heating systems-so-called hybrid systems-also offer potential in multi-story buildings in Uzbekistan. These systems can reduce heat consumption from the central grid or gas by 30–50%.

Hot water supply (DHW). Hot water production is a year-round requirement, which heat pumps (HPs) can provide much more economically than electric boilers. Specialized HPs for DHW production exist, particularly common in Japan (EcoCute) and Europe. They extract heat from indoor or outdoor air and heat the water in a tank to 55 – 60°C (CO_2 models - up to

90°C). In residential buildings, they are advantageously used in conjunction with storage water heaters, especially if multi-tariff electricity metering is available (the HPs heat the water at night). For Uzbekistan, where DHW is traditionally supplied by gas or electric water heaters during the warm season, switching to heat pump water heaters would yield significant energy savings (up to 70-75%, according to estimates, compared to heating elements) [6]. A reliable power supply is essential, as outages or low voltage hinder the use of HPs. However, as the energy system modernizes, the potential for using HPs for DHW production increases. Compared to an electric boiler, a heat pump consumes several times less electricity to generate the same amount of heat. For example, a modern pump generates approximately 4 kW of heat with a consumption of 1 kW, while a heating element only produces 1 kW.

Air conditioning and ventilation. As noted, most air conditioning systems are essentially heat pumps, pumping heat from the room to the outside in summer and vice versa in winter (if a reversible mode is available). Therefore, residential and commercial air conditioners are also part of the heat pump industry. In the hot climate of Uzbekistan, enormous amounts of power are expended on electric air conditioning in summer. Modern inverter air conditioners have a high EER (cooling efficiency ratio) of ~3-4, which is equivalent to operating as heat pumps with a coefficient of performance (COP) of 3-4 in cooling mode and significantly reducing the load on the power grid compared to a hypothetical electric heating/cooling system using resistance. Furthermore, there are heat pumps for ventilation heat recovery; for example, in large buildings, some of the heat from the exhaust air can be recovered through heat pumps to reheat the supply air or to heat the domestic hot water. Such units (called heat pump heat recovery units) are used in swimming pools, sports complexes, and shopping centers. They simultaneously dehumidify air and extract excess heat. In Uzbekistan, such solutions are still rare, but as the construction of high-rise buildings with combined supply and exhaust ventilation increases, energy efficiency will become a pressing issue.

Other utility applications. These include heat pump dryers for household use (there are heat pump dryers that consume 2-3 times less electricity), heat pump ground heating systems for outdoor sports fields (to prevent icing), snow melting on sidewalks, and others. These are specialized applications that could eventually find a niche in Uzbekistan, especially in terms of energy savings in the utility sector.

In summary, heat pumps (HPs) are a versatile tool for creating a comfortable and energy-efficient environment in the housing and utilities sector. They provide heating, cooling, and hot water with minimal energy consumption and are increasingly being implemented. For Uzbekistan, the most obvious areas of application for HPs in the near future include autonomous heating of individual buildings (schools, hospitals, cottages) in rural areas, particularly as a substitute for coal and fuel oil; hybrid systems in cities to reduce natural gas consumption; and air conditioning systems with HPs to reduce summer peaks in grid load [18].

Agriculture. In the agricultural sector, heat pumps are primarily used in processes requiring both heat and cold. Here are some typical applications.

Drying installations. Drying grain, fruits, vegetables, and medicinal herbs is an energy-intensive process traditionally accomplished by burning fuel or electric heaters. The use of a heat pump (HP) significantly improves drying energy efficiency. The HP extracts moisture and heat from the circulating air of the dryer and returns this heat to the process, consuming only electricity for heat transfer. Such HPs are particularly effective in the final stages of drying (when product moisture drops and conventional dryers lose efficiency). Farm-scale grain dryers with HPs have been developed in Russia and Kazakhstan. For example, Rudobashta S.P. et al. (2018) [20] described a grain drying unit with a heat pump heat exchanger, which reduced fuel consumption and ensured a more gentle temperature regime for grain drying. In Uzbekistan, where horticultural and grape produce are common, heat pumps could be used to dry fruits (apricots, grapes, etc.), ensuring high quality through low-temperature dehydration. Furthermore, the combination of a solar collector and a heat pump is ideal for drying. During the day, the collector heats the air, and at night, a heat pump maintains the process using the accumulated heat. This design was studied by O.F. Safarov's group (2009) [21] -they conducted an exergy analysis of a heat pump drying system with a solar collector and demonstrated its high efficiency in the Central Asian climate.

Greenhouse farming. Greenhouses require both heating in cold weather and cooling/ventilation in hot weather. A heat pump can operate in two modes, ensuring year-round maintenance of the microclimate. In winter, it extracts heat from the ground or outside air and heats the greenhouse, while in summer, it removes excess heat (cools). Furthermore, the heat removed in summer can be accumulated in the ground (for example, with the GeoCool system), increasing the

efficiency of winter heating -a principle of seasonal heat storage. In Russia, as early as 2006, trials of a heat pump system for maintaining the microclimate of greenhouses were reported. Calculations show that a ground-source heat pump combined with a system of warm ground pipes in a greenhouse can reduce heating costs by up to 50%. In Uzbekistan, given the abundance of solar energy, the "solar greenhouse + heat pump" scheme is an interesting option. Solar collectors heat water during the day, and heat pumps maintain the temperature at night, which evens out the temperature and reduces the need for gas combustion. Some farms are already experimentally using heat pumps in greenhouses, but widespread adoption is hampered by the low cost of coal and gas and a lack of awareness among farmers about new technologies.

Livestock farms. Heat pumps can be used to heat animal buildings (pig houses, poultry houses) in winter and cool them in summer. They are also effective for recovering heat from ventilation air on farms. For example, a heat pump heat recovery unit can warm the supply air using heat removed by the exhaust hood, especially during cold periods. Another application is milk cooling on farms; milking cows requires rapid cooling of milk to $+4^{\circ}\text{C}$. Refrigeration units with heat pumps can simultaneously cool milk and heat water (for sanitary purposes), thereby increasing the overall efficiency of the unit. In EU countries, such systems are standard on dairy farms (so-called milk-cooler heat pumps).

Storage of crops. Storing fruits, vegetables, and potatoes requires cold storage with controlled temperature and humidity. The heat pump in such storage acts as a refrigerator, removing heat. However, during the off-season, when the outside temperature is close to the required level, it can operate in economizer mode or use the soil as a buffer. A promising solution is a soil-based heat pump. In summer, it accumulates "cold" in the soil and releases it in winter (for example, when storing apples). Literature describes implementations of such systems with energy savings of up to 30% [13].

In summary, heat pumps (HPs) are a very promising technology in agriculture for improving energy efficiency and product quality (gentle drying, climate control). Particularly important is that they can be powered by renewable sources (solar panels, biogas plants -through electricity generation) and do not require fossil fuels on-site. In Uzbekistan, with its hot summers and abundant solar energy potential, HPs can be used in drying fruit and vegetables, energy-efficient vegetable storage facilities, and greenhouses. Uzbek scientists have already conducted successful

research in this area, but further practical testing of these technologies and government support for pilot projects are needed.

Key scientific achievements and progress in heat pump technology. Over more than a century of heat pump technology development, significant scientific advances have been accumulated. We will examine key advances in various areas -from theoretical thermodynamics to design solutions and optimization methods.

Development of the theory and improvement of efficiency (thermodynamics). The theoretical foundations of HP were laid by scientists of the 19th century (Clausius, Thomson, etc.) [22, 23] through the analysis of the reverse Carnot cycle. However, the applied theory of HP began to take shape in the 20th century, when it became necessary to compare their efficiency with traditional systems. The concept of the coefficient of performance (COP) was introduced -the ratio of the heat given off to the consumer to the work expended by the compressor. It was shown that the maximum COP is limited by the Carnot cycle and depends on the temperatures of the hot and cold reservoirs. In the 1970-80s, the calculation base for heat pump cycles was actively developed. In addition to idealized models, models took into account real irreversibility, leaks, incomplete condensation, etc. appeared. In the USSR, a significant contribution to the development of the theory was made by the Odessa school (L.I. Morozyuk et al.) [13], who generalized the theory of refrigeration machines and HP in their fundamental work of 2006. This monograph covers all aspects, from thermodynamic analysis to methods of cycle synthesis and optimization of modes.

One of the most important scientific achievements was the introduction of exergy analysis for heat pump systems. Exergy (irreversibility) analysis allows for a quantitative assessment of where and how much "thermodynamic perfection" is lost-in the compressor, throttle, and heat exchangers. By the end of the 1970s, the first works devoted to the exergy assessment of heat pumps had appeared. For example, Yu. V. Pustovalov, in 1982, performed an exergy analysis of a vapor-compression heat pump unit with an electric drive [24]. In 1989, V. P. Protsenko and V. K. Safonov [25] introduced the concept of exergy efficiency of heat pump cycles and analyzed it for various schemes. Exergy efficiency characterizes the degree to which a real cycle approaches the ideal reverse Carnot cycle. These studies showed that the main exergy losses occur in the compressor and throttling device, as well as during heat exchange with finite temperature differences. Based on these findings, the design of heat

exchangers was improved (the surface was increased, regenerative circuits were used) and control methods were proposed that reduce irreversibility (for example, multi-stage throttling with intermediate boiling).

The next step is the development of an exergoeconomic approach. This combines exergy analysis with economic analysis, enabling system optimization taking into account energy and equipment costs. In the early 2000s, studies appeared in the Russian literature using the total present value, expressed in terms of exergy, as the optimality criterion [26]. These studies helped find optimal balances between capital investments (increasing heat exchanger surface area, using more expensive compressors) and operating costs (electricity consumption). In particular, it was shown that there is often an optimal superheat at the compressor inlet and an optimal compression ratio at which total costs are minimal-after which, the energy savings do not offset the increased equipment cost.

Finally, we note advances in modeling and computational methods. Modern scientific tools, such as CFD (numerical flow and heat transfer modeling), enable detailed analysis of flows in compressors, ejectors, and complex heat exchanger geometries. For example, S.V. Artemenko et al. [27] performed computer modeling of the gas dynamics of ejector heat pumps, revealing ways to improve the efficiency of steam ejector circuits. This made it possible to create ejector refrigeration units with improved COP due to the recovery of throttling losses. Equations of state for new refrigerants, multi-parameter optimization methods, modeling of control system dynamics, etc. are being implemented in heat pump cycle calculations. All this forms a modern theoretical basis for the further improvement of heat pumps.

Design and technological advancements. Over the past decades, VT designs have undergone significant changes, significantly improving their reliability and efficiency and expanding their range of applications.

Compressor improvements. Historically, the first heat pump systems used piston compressors (like those found in refrigerators). Currently, the range of compressor solutions used has expanded significantly and includes scroll compressors with high energy efficiency and low noise levels, screw compressors for industrial applications, and oil-free turbochargers with magnetic bearings used in systems with increased COP requirements. A key step has been the introduction of drives with smooth speed control (inverters) - this allows the compressor to operate optimally at partial loads. For example, in Japan and Europe, since the 2000s, virtually all domestic heat pumps have been

inverter-based, which increases their seasonal efficiency by 20-30%. Research into the performance of modern compressors is also underway in Russia. For example, E.Kh. Shungarov et al. (2020) [28] studied the performance of scroll compressors for low-temperature air-source heat pumps. It has been shown that optimizing the design of the scroll unit and electric motor allows for maintaining operability down to outside temperatures of -30°C . Overall, the development of compressor technology is one of the cornerstones of HP progress.

New Refrigerants and Cycles. Following the phase-out of CFC and HCFC refrigerants (such as R12 and R22), the industry transitioned to HFCs (R134a, R410A, R407C, etc.). However, global warming concerns require a transition to acceptable refrigerants. Significant progress has been made in the use of CO_2 (R744) -although its cycle requires high pressures and is transcritical, Japanese engineers have succeeded in creating reliable CO_2 systems for domestic hot water. This discovery solved the problem of heating water to high temperatures without electrical reheating [7]. At the same time, interest in ammonia (R717) has returned as a natural refrigerant with excellent thermodynamic properties (it is used in large industrial heat pumps, for example, in dairies and municipal heating plants). New blends have also emerged - hydrofluoroolefins (HFOs), such as R1234ze, with very low GWP, which are planned for use instead of R134a in chillers and heat pumps. The development of optimal blended refrigerants is a separate scientific task, where zeotropic blends are selected that provide a sliding temperature during the phase transition. Such blends allow for better matching of temperature curves in condensers/evaporators, increasing the average COP. In Russia, research is being conducted on heat pump cycles using zeotropic blends -for example, Garanov S.A. et al. (2019) [29] described an aut cascade heat pump using a blend with a "sliding" boiling point. Improvements in refrigerants have also led to cycle modifications. Cycles with an internal heat exchanger, two-stage compression cycles, and steam-water ejector cycles have all been introduced - all aimed at increasing efficiency. For example, water-ejector thermal transformers were investigated by Shcherbakov V.S. (1994) [30] - they made it possible to utilize low-boiling mixtures with high efficiency.

Improving Heat Exchangers. Heat exchangers (evaporators and condensers) are key components affecting COP. In recent years, there has been a shift from tubular designs to aluminum microchannel heat exchangers, which offer lower thermal resistance and reduce refrigerant charge. Specialized plate

evaporators for handling humid air are being developed, featuring anti-surge circuits for uniform liquid distribution, which increases reliability. Adaptive evaporators with area control (disabling some sections at low loads to prevent freezing) have also come into use. In the field of heat pump dryers, the concept of two-stage condensers has emerged. In the first stage, moisture is condensed from the air in the primary condenser, after which the air is additionally heated in the second condenser, allowing for simultaneous dehumidification and heating of the air flow for the drying process. All these solutions are the result of applied research in the field of heat exchange and mass transfer.

Automation and control. A modern heat pump is a complex automated system. Significant advances have been made in the development of control algorithms. Adaptive regulation of the coolant temperature depending on the outside temperature (climate control) and demand response (Demand Response)-when the heat pump is activated at a specific time of day by a signal from the power grid to smooth out peak loads-are being implemented. Many heat pumps are now connected to the Internet (IoT) and can be controlled via cloud services, ensuring the optimization of the unit fleet. From a scientific perspective, mathematical models of the thermal regime of buildings with heat pumps for predictive control are being actively developed. Kubota S. et al. (2020) [31] proposed a model for automated control of the thermal regime of a building with heat pumps, which takes into account the thermal inertia of the building and the weather forecast, reducing the number of compressor starts and increasing the overall service life of the unit. Automation topics have also found a response in Uzbekistan. Khamov A. Yu. and co-authors (2011) [32] examined the power supply and automation of heat pump systems, proposing methods for increasing power supply reliability and providing backup in case of power outages. It is important to emphasize that the heat pump automation system not only maintains temperature-it monitors refrigerant pressure, prevents emergency conditions (evaporator freezing, compressor overheating), and switches to optimal defrost modes. The development of remote diagnostic systems is another advancement, as modern heat pumps can automatically signal a decrease in refrigerant charge, clogged filters, and other problems, simplifying maintenance.

Comprehensive reliability and service life. Thanks to advances in materials and design, compressor service life has increased to 15-20 years of continuous operation. This was largely due to the development of

hermetic and scroll compressors with low vibration and good lubrication. Improved refrigerants (such as synthetic oils for HFCs) have also reduced wear. Many of the teething problems of early HPs have been addressed -fan noise has been reduced by specially shaped blades, frame design reduces vibration transmission to the building, etc. For example, in Switzerland, the aforementioned pump from 1938 is still in operation (in test mode) -80+ years later, albeit with a new compressor [6]. Modern units, however, are designed for tens of thousands of hours of service.

Thus, engineering advances have significantly advanced heat pumps. Modern units are 50-70% more efficient than 30-year-old models, with comparable or lower noise levels, greater reliability, and greater environmental friendliness. For example, while in the 1980s, a typical air-source heat pump had a seasonal COP of ~2, today the best models achieve a seasonal COP of >4 in temperate climates, and experimental systems achieve a COP of 6 or higher [6]. Heat pump design has embodied many innovations in refrigeration technology, and this evolution continues.

Exergoeconomics and system optimization. The current stage of development of heat pump science is unthinkable without an interdisciplinary approach -a combination of thermodynamics, economics, and ecology. Exergoeconomics, mentioned above, has become an important tool for scientific analysis. It is used to study not only individual heat pumps but also energy systems with heat pumps. For example, an exergoeconomic analysis of a "gas turbine + heat pump + refrigeration unit" system allows for the optimal distribution of energy flows between the components, minimizing the cost of generating cold and heat. In the works of Russian scientists (Vasiliev G.P. et al., 2019) [33], the efficiency of heat pump heating systems was analyzed from a climate and economic perspective. Their conclusion is that the use of even the least efficient heat pumps is economically justified given rising hydrocarbon prices, especially in the Far North, where imported fuel is very expensive.

In addition to exergoeconomics, mathematical modeling and optimization are actively used - methods of linear and nonlinear programming, genetic algorithms, the search for Pareto-optimal solutions for multi-criteria problems (for example, maximum exergy efficiency and minimum cost simultaneously). Such approaches are used in the planning of large projects - for example, the optimization of the configuration of a heat pump heating network for an entire city. Candidate of Technical Sciences S.A. Einstein in a series of articles from 2000-2001 [34] conducted the optimization of heat pump systems in

chemical engineering processes, essentially solving the problem of optimal distribution of the heat drop between compression and absorption. Similarly, for urban infrastructure - Nakoryakov V.E. et al. [35] were engaged in the modeling of a single water circuit with local heat pumps, demonstrating that optimization at the system level can provide 10-15% savings compared to the optimization of each pump separately.

Another area of focus is standardization and testing. Research centers have developed testing methods for various conditions (EN 14825 for calculating seasonal SCOP/SEER indicators; ISO 13256 for testing water/ground heat pumps; GOST R 54860 for testing methods and determining energy performance), which has enabled objective comparisons of devices from different manufacturers and stimulated competition in efficiency.

Advances in environmental assessment (LCA - life cycle analysis) are also worth mentioning. It has been found that HPs have a significantly lower carbon footprint than boilers: despite the energy required to produce the compressor and refrigerant, they save significantly more CO₂ over their lifespan. However, leaks of refrigerants such as R410A can reduce these environmental benefits, so researchers are seeking balanced solutions-for example, minimizing recharge, using natural refrigerants, and organizing the collection and recycling of working fluid from used units.

To summarize this section, we note that scientific progress in the field of heat pumps over the past decades has been comprehensive. Theory (exergetics) has provided an understanding of the limits of perfection, new materials and designs have brought devices closer to these limits, and optimization approaches and economics have ensured the implementation of the best solutions in practice. As a result, the heat pump, an engineering curiosity of the early 20th century, has evolved into a high-tech product of the 21st century, capable of playing a key role in the global energy sector.

Current tasks and challenges for the development of the heat pump industry. Despite the progress achieved, the heat pump industry today faces a number of scientific, technical, and applied challenges. Let's consider the most pressing of these, both globally and in light of the specifics of Uzbekistan.

Global scientific and applied problems

Increasing the temperature and capacity of heat pumps. Complete decarbonization of industry requires replacing boilers generating steam at 120-150°C and recovering the heat from high-temperature process streams. Modern vapor-compression heat pumps are

typically limited to ~70°C (up to 90°C for CO₂ systems). Therefore, the development of new cycles and working fluids that can achieve higher temperatures is essential. Research into two-stage and cascade systems (e.g., ammonia + propane) and new refrigerants is underway in this area. The goal is to create an industrial heat pump capable of operating at 120°C+ with a COP of at least 2.5-3. This solution will require both new compressors (e.g., two-stage screw compressors with interstage cooling) and materials (seals capable of operating at high pressures and temperatures). Some progress has already been made. For example, pilot units using R718 (water vapor) with jet compressors for heating up to 120°C have been produced, as have reactive heat pumps using chemical reactions. However, before these solutions can be widely adopted, they still have to go from the laboratory to a commercial product.

Low-freezing external heat sources. For air-cooled heat pumps, freezing of external heat exchangers in damp, frosty weather remains a pressing issue. Defrosting leads to energy losses and reduces seasonal COP. Researchers are working to find ways to prevent icing (special coatings, ultrasonic vibration, cycles with an intermediate refrigerant that prevents surfaces from reaching the dew point, etc.). Research is also underway to develop new anti-icing control algorithms. An intelligent system can adaptively select defrosting times based on sensor data and weather forecasts, minimizing their frequency. This solution is especially important for northern countries and, incidentally, for the mountainous regions of Uzbekistan, where humidity is high.

Widespread adoption of natural refrigerants and new blends. Over the next 10-15 years, the industry must phase out high-GWP HFCs (e.g., R410A with a GWP of ~2000), which means switching to R290 (propane), R744 (CO₂), R717 (ammonia), and new HFOs. Each of these substances requires appropriate adaptations to the heat pump design. Propane is flammable, requiring increased system tightness and a minimum refrigerant charge volume. CO₂ is characterized by high operating pressures, necessitating the use of reinforced compressors and specially designed heat exchangers. Ammonia is toxic and flammable, so its use is generally limited to industrial installations. New blends such as R454B (GWP ~400) and R32 (GWP ~675) are a compromise, albeit a temporary one. The scientific challenge is to find optimal, safe refrigerants, possibly azeotropic blends, that combine low GWP, nonflammability, and high refrigeration efficiency. At the same time, components (compressor oils, seals, sensors) must be

adapted to these new operating environments. The international community has set a goal of transitioning to refrigerants with a GWP<150 in household and commercial appliances by the 2030s, and research in this area is very active [7].

Improving integration with the power grid (Smart Grid). As the fleet of heat pumps grows, their impact on the power grid increases. The challenge is to avoid peak loads and instability. Smart control systems are being developed in this regard. Multiple heat pumps are being combined into a virtual power plant that can smooth out its overall consumption curve. For example, projects are underway in Europe to integrate heat pumps into a dispatch system. When there is an excess of renewable energy, heat pumps will be activated and heat storage tanks, and temporarily shut down during peak loads. The scientific challenge is to create algorithms that guarantee consumer comfort while allowing grids to "sag" heat pump loads without causing damage. This involves weather forecasting, occupant behavior patterns, cybersecurity, and other factors. Communication and control standards (protocols that allow the grid operator to send signals to household heat pumps) are also required.

Expanding application areas. Even today, there are niches where heat pumps are rare—for example, multi-story apartment buildings with centralized systems. Adapting heat pump technologies to dense urban environments is a priority. Possible solutions include compact building-mounted heat pumps that utilize heat from ventilation exhausts, or anthropogenic heat sources (subways, tunnels, wastewater). The IEA notes that it is urgent to expand the use of heat pumps in multi-story and commercial buildings [3], otherwise the pace of decarbonization will slow. Consequently, new configurations are needed—for example, fanless heat pumps for indoor installation (to minimize outside noise), or split systems with remote heat exchangers on roofs/basements. Each such case requires a separate engineering research effort.

Reducing capital expenditures and expanding production. The cost of heat pumps remains a barrier, as on average, installation of a heat pump is more expensive than a gas boiler (although the cost savings offset this). Transitioning from a niche market to a mass market requires a price reduction. This is achieved through increased production (economies of scale) and new technical solutions. For example, simplifying installation operations—currently, geothermal heat pumps require well drilling, which is expensive. Research is underway on alternative ground collectors (for example, driven ground probes,

which are faster and cheaper to install). Another approach is modular heat pumps, produced in large series (up to >100,000 units per year, like air conditioners). Researchers should consider finding cheaper materials and designs, possibly eliminating expensive copper (microchannel aluminum heat exchangers), using plastic pipes, 3D printing complex compressor parts, etc. High hopes are placed on increasing competition in the market. Currently, the top 5 manufacturers control a significant share (and all are based in Asia) [3]. Expanding production geography, including the creation of new companies, can reduce prices. From a scientific perspective, standardization and project categorization are important so that engineers planning heating systems with heat pumps can use proven solutions rather than designing them individually.

Training and consumer education. Although this task is primarily social, it is also supported by research—for example, studying consumer perceptions of heat pumps, barriers to implementation, and developing training programs. Installers, service engineers, and designers must be trained; without this, even the best heat pump can be installed incorrectly and be ineffective. Scientific conferences and publications provide space for the exchange of implementation experiences and the development of recommendations for different climate zones and building types.

Overall, the global community understands that heat pumps are an integral element of a future carbon-free energy system and is actively working to remove remaining barriers. As the IEA's 2023 report noted, to achieve climate goals by 2030, heat pump sales must double, and by 2050, more than three-quarters of the world's heating must be provided by electric heating systems [3]. These are ambitious targets, and achieving them requires addressing the challenges described above.

4. Discussion

Priority Tasks for Uzbekistan. For Uzbekistan, general global challenges are complemented by specific national circumstances. Below are the most pressing scientific, technical, and applied challenges facing the country today as it implements TN.

Adapting heat pump technologies to the local climate. Uzbekistan has a sharply continental climate. In winter, temperatures in the northern and central regions can drop to -20°C and below, while in summer they often exceed +40°C. These extremes place special demands on heat pumps. The challenge is to select and adapt the optimal heat pump types for these conditions. In colder regions (Tashkent and Syrdarya regions), ground-source or water-source heat pumps,

which are less susceptible to frost, are likely the best solution. In the southern regions (Termez and Navoi), where winters are milder, air source heat pumps can be effectively used for heating, and their ability to cool in the summer is an additional advantage. A climate analysis should be conducted to determine how many hours per year a given heat pump type will operate effectively. Scientifically based recommendations can be incorporated into building codes - for example, when designing new residential areas, zoning should be considered for the appropriateness of heat pump use.

Developing pilot projects and demonstrations. One barrier to implementation is the lack of demonstration facilities. Pilot projects are needed in various sectors to locally test the technology and collect data. Pilot heat pump systems for heating rural schools (such as the one implemented in Syrdarya) are a successful example [5]. It would be desirable to expand the geographic scope. For example, install a demonstration heat pump in the Fergana Valley (where it is colder and gas supply is more difficult), and another in Karakalpakstan (where there are problems with centralized heating and coal was used). Heat pumps should also be tested in an industrial pilot zone-for example, at a specific thermal power plant-to assess the impact on the energy sector. It is important that these projects be supported by scientific organizations; COP and fuel savings must be measured, failures must be analyzed, and personnel must be trained. The results will allow for further strategic adjustments.

Economic efficiency and financing. While natural gas prices are low (subsidized), heat pumps may struggle to pay for themselves. However, this is changing: tariffs are planned to gradually align with global levels. Even with current electricity and coal tariffs, analysis demonstrates acceptable payback periods for heat pumps in schools (~5-7 years with subsidies) [5]. Economists must now thoroughly calculate the exergoeconomic indicators of heat pump implementation in various conditions in Uzbekistan. The social impact (improved environmental conditions due to the transition from coal and consumer convenience) must also be taken into account. It seems appropriate to consider developing incentive mechanisms for heat pump implementation, including the provision of preferential loans for their installation, tax incentives in the form of exemptions from value-added tax, as well as direct subsidies and pilot grant programs. In this context, scientific research directly impacts public policy, as the results obtained allow for the substantiation of recommendations for the

selection of the most effective government support measures. For example, in rural schools, the savings from switching to heat pumps and solar panels can be measured not only in financial terms, but also in improved children's health (no coal smoke) -this is difficult to assess, but it is an important effect.

Developing a regulatory framework and standards. Uzbek building codes barely mention heat pumps. Amendments are needed. For example, allowing the use of heat pumps in apartment buildings and defining noise, vibration, and safety requirements (especially when using refrigerants such as propane) are essential. Heat pump testing standards are needed for the Central Asian climate, possibly tailored to higher temperature ranges. In the future, with widespread development, benchmarks could be established. For example, new buildings of a certain energy efficiency class must be equipped with heating systems with at least a certain efficiency factor (which effectively encourages the use of heat pumps). The development of such standards should be carried out by specialized research institutes in collaboration with the Ministry of Energy and the Ministry of Construction of the Republic of Uzbekistan, drawing on scientific data and the experience of other countries.

Research on the most promising technologies in the context of Uzbekistan. Available natural resources should be taken into account. Uzbekistan is rich in solar energy, so it makes sense to develop solar-heat pump systems. Back in Soviet times, the Physics and Technology Institute of the Academy of Sciences of the Republic of Uzbekistan conducted unique research on combining solar collectors with heat pump units. Resuming this work could make Uzbekistan a leader in combined systems optimal for arid climates. Another unique feature is geothermal resources. The republic has areas with thermal waters (for example, the Chimgan field), although not at very high temperatures. However, instead of directly using these waters for heating (which is problematic due to deposits and corrosion), absorption or compression heat pumps can be used to pump heat from geothermal water. This scheme (geothermal water ~40-60°C -> heat pump -> heat transfer fluid 80°C) would make it possible to exploit even moderately warm springs. Geothermal heat pump stations are successfully operating in Iceland and Turkey, for example. In Uzbekistan, this idea could be tested at small fields in the Fergana Valley. The research objective is to select appropriate cycles (possibly an ammonia-water absorption heat pump, which operates optimally at a 60°C source).

Localization of HP production. For long-term development, it would be beneficial to organize at least partial production or assembly of HPs in the country. It would be possible to establish production of simple air-cooled heating units (demand for these could be massive as interest grows). For example, local production could begin with licensed assembly of medium-capacity HPs for social facilities, which could stimulate the economy and reduce costs for consumers.

In summary, the most important thing for Uzbekistan is to integrate global advances into national practice, while simultaneously addressing specific challenges. Political will and coordination among science, business, and government are essential for TN to find their place in the country's energy system.

Promising areas of research and implementation in Uzbekistan. Based on the objectives discussed, several priority research areas and the most promising areas for the implementation of heat pumps in Uzbekistan in the coming years can be identified. These areas take into account the country's climatic conditions, energy consumption structure, and economic realities.

Hybrid heating systems for homes. The most rational approach will likely be the phased introduction of hybrid heat pumps, in conjunction with existing heat sources. Uzbekistan is characterized by the widespread use of gas boilers in homes. Their complete replacement with electric heat pumps is difficult in the short term (due to grid constraints and investment). However, installing an air or ground source heat pump in parallel with the boiler, covering 60-80% of the annual heat demand, already looks attractive. The heat pump would operate at outdoor temperatures above, say, -5°C , and in even colder temperatures, the boiler would automatically engage. Research should determine optimal management strategies for this combination and their cost effectiveness (for example, in Italy, hybrid systems have received subsidies for saving gas). In local conditions, this would significantly reduce gas flaring in the fall and spring, and reduce gas consumption in winter. The potential is to use the existing gas infrastructure only to cover peaks and as a backup, with electric heating for most of the season. This also fits into the concept of energy transition (gradual electrification).

Solar-heat pump power systems. As noted, the combination of solar energy and heat pumps is particularly relevant for Uzbekistan, with its high levels of insolation. The creation of autonomous energy complexes for rural areas, combining a solar photovoltaic power plant (PVP) and a heat pump for

heating/cooling, is promising. During the day, electricity from the sun powers the heat pump, with excess energy stored in a heat accumulator (e.g., a large water tank). At night, the heat pump can be partially powered by batteries or the grid, but the load on the grid will be minimal. Such a "HP+PVP" system has already been tested as part of a GEF project [36], where solar panels offset the increased electricity consumption of the heat pump. The results showed that with properly sized PVP power, it is possible to cover a significant portion of the heat pump's electricity needs and reduce specific costs. Further research is needed to optimize the size, in particular how to correlate panel area, battery capacity, and heat pump power for different types of facilities (schools, farms, homes). Uzbekistan has ambitious goals for the development of solar power generation, and heat pump systems can become a natural consumer of this energy on-site, smoothing out daily fluctuations in generation (accumulating heat during the day and dissipating it at night).

Geothermal HPs and ground source heat recovery. Another promising area is geothermal HPs, both small and relatively large. Firstly, these are individual heating systems based on vertical ground probes. Even in the absence of surface geothermal water, typical ground at a depth of 50-100 m in Uzbekistan has a temperature of $\sim 15^{\circ}\text{C}$ year-round. This "free" heat can be effectively utilized. Experiments with drilling small-diameter boreholes and installing U-shaped pipes for ground source HPs in different regions of Uzbekistan are worthwhile to obtain data on the thermal conductivity of the soil and optimal filling (water, antifreeze). Secondly, there are geothermal springs (e.g., Chartak, Yangibazar, etc.) that produce water at a temperature of $40-60^{\circ}\text{C}$. This is insufficient for direct heating, but a HP can increase the temperature to the required 80°C . There are examples of successful use of low-potential geothermal waters through HPs worldwide (in Germany and China). A demonstration project is promising. For example, heating a sanatorium or greenhouse from a geothermal well using an absorption-compression heat pump (these hybrids are particularly effective when hot water and electricity are available). Developing this approach would allow for the diversification of Uzbekistan's energy resources and the use of renewable heat from the Earth, of which the country has abundant resources.

Low-grade heat recovery in industrial plants. Uzbekistan's industry (chemical plants, metallurgy, and thermal power plants) has so far paid little attention to heat pumps. However, the potential here

is significant. For example, at combined heat and power plants (CHPs), the heat of condenser exhaust water can be recovered (as discussed above), resulting in gas savings and increased heat output. Chemical plants (Ammophos, Navoi Mining and Metallurgical Plant) have processes where some flows are cooled while others require heating. In these cases, compressor or ejector heat transformers can be advantageously integrated. Conducting energy audits from an exergy perspective could identify specific areas where the use of heat pumps would be beneficial. A promising area of research is vapor-compression heat exchangers to replace throttle-thermostatic valves in rectification and evaporation units. Domestic scientists (V.G. Einstein et al.) [34] wrote about compensating heat pumps in chemical engineering as early as the 2000s. Resuming this work, taking into account modern components, could lead to the development of domestic prototypes of industrial heat pumps (for example, a 0.5 MW steam compressor operating on secondary boiler steam). An important specific case is refrigeration units in food production, especially those with a simultaneous heat requirement. Such projects have been implemented abroad and pay for themselves within 1-2 years; this is also possible in Russia.

Improving the urban ecology and microclimate through heat pump technologies. Tashkent and other large cities face the problem of winter smog due to private coal-fired boilers and exhaust fumes. Converting at least some of the heat production to electric heat pumps (provided they are "green") will improve air quality. For example, equipping public buildings-schools, kindergartens, and clinics-with heat pumps is a promising option. These buildings are typically heated by gas or even coal in rural areas, which creates smoke. A GEF pilot project at a school demonstrated not only an energy benefit but also a social one-clean air in classrooms [5]. Disseminating these solutions is an important goal. Furthermore, heat pumps can contribute to improving the urban microclimate in summer. Their high efficiency makes it possible to more widely implement central air conditioning in residential buildings (individual air conditioners are currently often used, discharging heat outside and warming the courtyard). A home cooling system using heat pumps could also dissipate the heat, for example, into the ground (for seasonal storage). Research into such seasonal heat and cold storage systems (for example, large water tanks heated in the summer and releasing the heat in the winter through a heat pump) is an interesting topic for Uzbekistan, where seasonal differences are significant. In Canada

and China, there are villages where solar heat is used to heat the ground beneath the block in the summer, and a heat pump extracts the heat from there in the winter. We have even more sun in the summer-it would be a shame not to utilize it. It would be promising to select a pilot site (a new eco-neighborhood) and test this technology there.

Establishing competence centers and local engineering. Implementing heat pumps requires more than just hardware; it also requires knowledge. It would be promising to establish a competence center for heat pumps at one of the technical universities, combining education, research, and consulting. It could conduct testing of new models (for example, certify imported heat pumps for Uzbekistan's conditions), develop software for calculating heat pump systems (taking into account our tariffs, climate, and regulations), and so on. The center could also collaborate with international organizations (IEA Heat Pump Centre) and promote the country's interests in this area. Local engineering-design adaptation, installer training-could all be concentrated, which would lower the barrier to technology entry into the market.

In conclusion, we emphasize that HPs offer Uzbekistan a unique opportunity to simultaneously address energy efficiency, environmental concerns, and improved living conditions. With sound scientific support and a government strategy, the country can make the leap from a traditional gas-based heating system to a modern, electrically controlled, and renewable energy-integrated model. The promising research and projects described above serve as a roadmap to this goal. By implementing them, Uzbekistan will not only improve its domestic energy system but also join the global trend of technological development, cementing its status as a progressive country implementing cutting-edge green technologies.

5. Conclusions

Heat pumps have undergone a long development path, from isolated pilot installations to a mass-market technology with a significant impact on modern global energy. This review shows that research into heat pumps has evolved in waves. It began with the first experiments in the early 20th century, was followed by a surge of interest in the 1970s, and has progressed to the steady growth and large-scale implementation observed since the 2010s. The identified stages-before the 1990s, 1990-2010, and after 2010-are characterized by shifts in research priorities and the scale of implementation, driven by technological evolution and

societal needs (energy crises, environmental agenda, etc.).

In practice, heat pumps find application in a wide range of sectors. In industry, they are used to recover waste heat, for drying processes, and for various technological operations. In the energy sector, heat pumps are used to improve the overall efficiency of power plants and integrate renewable heat sources. In the housing and utilities sector, they are used for heating, cooling, and hot water supply to buildings, as well as within heating networks. In agriculture, heat pumps are used in greenhouse heating systems, drying systems, and on farms. Their implementation provides significant energy savings and environmental benefits [6]. Specific examples from domestic literature and international experience are provided, demonstrating the versatility and efficiency of heat pumps -from urban heating based on low-potential sources to fuel-efficient farm grain dryers.

Scientific advances encompass both fundamental aspects (thermodynamics, exergetics) and engineering solutions (new compressors, refrigerants, cycles). Heat pump theory now includes exergoeconomic analysis and multiparameter optimization, enabling the creation of units with efficiency levels approaching the Carnot limits [6]. Design advances-inverter compressors, microchannel heat exchangers, transcritical CO₂ cycles-have led to a doubling or more of efficiency factors over the past 30 years. Advances in automation and control have transformed heat pumps into "smart" elements of the energy system, capable of participating in load balancing. The work of Russian scientists (Protsenko, Kalnin, Morozyuk, Elistratov, and others) has played a significant role in contributing to the theory and practice of heat pumps.

Current issues reflect the remaining challenges. It is necessary to develop hotter and more powerful heat pumps for industry, switch to natural refrigerants, improve heat pump performance in extreme climates, integrate millions of pumps into power grids without sacrificing stability, reduce their costs, and train personnel. Addressing these challenges is a priority on the international agenda, as evidenced by IEA programs and the rapid market growth [3]. Particular attention is being paid to replacing fossil fuels in heating -electric heat pumps are recognized as a key tool for reducing the carbon footprint of the domestic and utility sectors [4].

Heat pumps are of great interest to Uzbekistan, although they require consideration of local conditions. The country's pressing challenges include adapting the technology to a continental climate,

demonstrating economic benefits in the face of cheap gas, and developing a regulatory framework and local expertise. Pilot projects (for example, heating schools and hospitals using the "HP+Sun" system) have already yielded positive results and should be expanded [5]. Scientifically substantiated prospects include hybrid "HP+gas" systems for cities, autonomous solar heat pump systems for rural areas, exploiting geothermal potential using HPs, and using HPs in industrial enterprises across the country. The success of these initiatives will allow Uzbekistan to reduce the burden on the gas industry, improve the environment, and ensure energy security.

Overall, the analysis shows that heat pumps represent a technology that combines fundamental thermodynamic principles and practical applicability across a wide range of heating applications. Coordination of scientific research, engineering practice, and public policy can create conditions for the wider adoption of heat pump technologies in Uzbekistan's energy sector. In the long term, this will yield dividends in the form of sustainable energy supply, reduced costs, and a contribution to the global fight against climate change.

This review does not exhaust the entire spectrum of research in the field of heat pumps, but it allows us to highlight key trends and the most promising areas of their application in the conditions of Uzbekistan.

References

1. New Buildings Institute. Hot Water Time Machine: The Cool History of Heat Pump Water Heaters. - Electronic resource. - URL: <https://newbuildings.org/hot-water-time-machine-the-cool-history-of-heat-pump-water-heaters/>
2. Dover DE HVAC Knowledge. The History of Heat Pumps. - Electronic resource. - URL: <https://www.griffithenergyservices.com/dover-de-hvac-knowledge-the-history-of-heat-pumps/>
3. Global heat pump sales rose by 11% in 2022, says IEA. - pv-magazine.com, 2023. - Electronic resource. - URL: <https://www.pv-magazine.com/2023/04/03/global-heat-pump-sales-rose-by-11-in-2022-says-iea/>
4. International Energy Agency (IEA). Uzbekistan: Energy efficiency and demand. - Electronic resource. - URL: <https://www.iea.org/countries/uzbekistan/efficiency-demand>
5. Economic analysis of heat pumps in a rural secondary school. - The GEF Small Grants Programme in Uzbekistan. - Electronic resource. - URL: <https://sgp.uz/ru/cost-benefit-analysis-heat-pumps-rural-schools-rus/>
6. Swiss Federal Office of Energy (SFOE). History of Heat Pumps: Swiss Contributions and International Milestones. - Electronic resource. - URL: <https://www.ehpa.org/wp->

- content/uploads/2023/07/History-of-Heat-Pumps-Swiss-Federation.pdf
7. Saikawa M. An Inside Story Behind the Advent of "Eco Cute" CO₂ Heat Pump Water Heater for Residential Use // Heat Pumping Technologies (HPT TCP). - Electronic resource. - URL: <https://heatpumpingtechnologies.org/publications/an-inside-story-behind-the-advent-of-eco-cute-co2-heat-pump-water-heater-for-residential-use/>
 8. European Heat Pump Association (EHPA). Heat Pumps in Europe: Key Facts & Figures. - 2023. - Electronic resource. - URL: https://www.ehpa.org/wp-content/uploads/2023/11/November-2023_HP-Key-Facts_compressed.pdf
 9. International Energy Agency (IEA). Heat Pumps - Energy system, 2023. - Electronic resource. - URL: <https://www.iea.org/energy-system/buildings/heat-pumps>
 10. Joint Research Centre (JRC), European Commission. Heat Pumps in the European Union. - 2025. - Electronic resource. - URL: https://joint-research-centre.ec.europa.eu/publications/heat-pumps-european-union_en
 11. Svenska Kyl & Värmepumpföreningen (SKVP). Pulsen 2024: prisnivåer för värmepumpar. - Stockholm, 2024.
 12. Avezova N. R., Sharipov K. A., Salomov U. R., Kuchkarbaev R. U., Shermatova M. B. Combined heat and cold supply systems with heat pumps and renewable energy sources in Uzbekistan // Innovative technologies. - 2025. - Vol. 58, No. 2. - P. 33-54.
 13. Morozzyuk T. V. Theory of refrigeration machines and heat pumps. - Odessa: Studio "Negotsiant", 2006. - 412 p.
 14. Einstein V. G., Zakharov M. K., Nosov G. A. Compensating heat pump in chemical-technological processes // Chemical industry. - 2000. - No. 9. - P. 454-462.
 15. Molodkina M. A. Improving the technical and economic performance of combined-cycle power plants by utilizing low-potential heat using heat pumps: Abstract of a PhD in Engineering Sciences. - St. Petersburg, 2012. - 201 p.
 16. Agababov V. S., Dzhuraeva E. V., Koryagin A. V. Comparison of gas heating methods in an expander-generator unit // Thermal Power Engineering. - 2003. - No. 11. - P. 46-50.
 17. World's largest zero-carbon 90°C district heat pump opens its doors. - Star Refrigeration. - Electronic resource. - URL: <https://www.star-ref.co.uk/news/worlds-largest-zero-carbon-90c-district-heat-pump-opens-its-doors/>
 18. Economic analysis of heat pumps in a rural secondary school. - The GEF Small Grants Programme in Uzbekistan. - Electronic resource. - URL: <https://sgp.uz/ru/cost-benefit-analysis-heat-pumps-rural-schools-rus/>
 19. Ovsyannik A. V., Rykhter O. L., Matsko I. I., Bobovich S. O. Prospects for the application of heat pump technologies in a district heating complex // Power Engineering. - 2008. - No. 8.
 20. Rudobashta S. P., Zueva G. A., Muravleva E. A. Farm grain drying unit with a built-in heat pump // Russian Chemical Journal. - 2020. - Vol. 90, No. 6. - P. 1163-1167.
 21. Safarov O. F., Radzhabov M., Komilov O. S., Abdurakhmanov O. R. Exergy analysis of a heat pump drying unit // Heliotechnics. - 2009.
 22. Clausius R. On the experience of thermodynamic movements. - Leipzig: BG Teubner, 1850. - 116 p.
 23. Thomson W. On the dynamical theory of heat // Proceedings of the Royal Society of Edinburgh. - 1852. - Vol. 10. - P. 182-185.
 24. Pustovalov Yu. V. Exergy analysis of a vapor compression heat pump unit // Proceedings of VNIPIEnergoprom. - 1982. - P. 39-53.
 25. Protsenko V. P., Safonov V. K. Exergetic efficiency of heat pump units // Bulletin of the USSR Academy of Sciences. Power Engineering and Transport. - 1989. - No. 1. - P. 123-130.
 26. Amerhanov R. A. Exergoeconomic optimization of heat pump systems // Energy saving and water treatment. - 2003. - No. 2. - P. 65-67.
 27. Artemenko S. V. Computer fluid dynamics of ejector heat pumps // Proceedings of the XIII school-seminar of young scientists. - M.: MPEI, 2001. - V. 1. - P. 362-365.
 28. Shungarov E. Kh., Ivanov A. V., Petrov B. S. Study of the operating characteristics of scroll compressors // Heat and Power Engineering and Refrigeration Engineering. - 2020. - No. 4. - P. 47-55.
 29. Garanov S. A., Zuev O. A., Ivanova E. V., Sukhov A. S. Autocascade heat pump on zeotropic refrigerant // The future of mechanical engineering in Russia. - Moscow: Bauman Moscow State Technical University, 2019. - P. 567-569.
 30. Shcherbakov V. S., Markanov M. A. Water-jet heat pumps // Refrigeration engineering. - 1994. - No. 5. - P. 23-26.
 31. Kuboth S., Heberle F., König-Haagen A., Brüggemann D. Experimental long-term investigation of model predictive heat pump control // Energies. - 2020. - Vol. 13, No. 22. - 6016.
 32. Khamov A. Yu., Kopyrin V. A., Novokreshchennykh E. V., Portnyagin A. L. Power supply and automation of a heat pump installation // Proceedings of the scientific and practical conference. - Tyumen, 2011. - P. 9-13.
 33. Vasilyev GP, Gornov VF, Kolesova M. Efficiency assessment of ground source heat pump systems // IOP Conference Series: Earth and Environmental Science. - 2019. - Vol. 249. - 012033.
 34. Einstein V. G., Zakharov M. K., Nosov G. A. Optimization of a complete heat pump // Chemical industry. - 2001. - No. 1. - P. 18-27.
 35. Nakoryakov V. E., Elistratov S. L., Bivalkevich A. I., et al. Autonomous heat sources based on wastewater heat // Energy efficiency program for the Novosibirsk region. - Novosibirsk, 2005. - P. 249-256.
 36. Rudenko I. Yu. Analysis of the benefits and costs of an alternative heating system (HP + PVS) for rural schools in Uzbekistan. - Tashkent: UNDP Uzbekistan, 2019.