VINNYTSIA NATIONAL TECHNICAL UNIVERSITY
MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

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DISSERTATION

IMPROVING THE ECOLOGICAL SECURITY OF URBANIZED AREAS THROUGH THE RATIONAL INTRODUCTION OF ENERGY EFFICIENT AND ENVIRONMENTAL TECHNOLOGIES IN THE FIELD OF HEAT SUPPLY

Specialty: 183 «Environmental Protection Technologies»
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Applying for the degree of Doctor of Philosophy

The dissertation contains the results of my own research. Using ideas, results and texts of other authors have a link to the corresponding source.

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ABSTRACT

Zhang Le. Improving the environmental safety of urbanized areas through the rational implementation of energy-efficient and environmentally friendly technologies in the field of heat supply. – Qualifying scientific work on the rights of the manuscript.

Dissertation for obtaining the scientific degree of Doctor of Philosophy in specialty 183 – "Technologies of environmental protection" (field of knowledge 18 – "Production and technologies"). – Vinnytsia National Technical University, Vinnytsia, 2025.

With the acceleration of global urbanization, the problems of energy consumption in cities and the environment are becoming increasingly visible. As an important part of urban infrastructure, energy efficiency and environmental friendliness of the heating system are directly related to the sustainable development of the city. According to statistics, the heating sector accounts for about 30% of global energy consumption, and this area is also one of the main sources of atmospheric pollution with harmful substances such as SO_2, NO_x, particulate matter, etc. Therefore, the issue of rational implementation of energy-saving and environmentally friendly technologies and energy-ecological optimization of the heating system has become the subject of considerable attention of modern academic and political circles.

The significant negative impact of municipal energy systems on the environment contributes to the development and intensification of local and global environmental problems, especially in urbanized areas. The operation of boiler plants and combined heat and power plants requires their provision with fuel, the need for which is increasing with the expansion of heating networks. In this regard, the problem of increasing the environmental and energy efficiency of municipal energy in the context of increasing its impact on the natural environment and urbanized areas and rising energy prices is highly relevant.

A new approach to solving this problem, which is used in the dissertation, is to combine the producer, supplier and consumer of thermal energy into a single technical complex for which the search for optimal technical solutions to increase its environmental, resource and economic efficiency with minimal investment costs is

carried out. Achieving such a result is ensured by the rational implementation of energy-saving technologies.

The dissertation sets and solves the current scientific and applied task of increasing the efficiency of greening municipal energy systems and improving the ecological state of urbanized areas by creating and verifying an improved method for the rational implementation of energy-saving technologies at objects that consume and produce thermal energy in the municipal sector.

The problem, the solution of which is devoted to the dissertation: reducing the negative impact of urban heat supply systems on the ecological state of urban areas.

The object of the study: processes of environmental pollution by emissions of harmful substances and greenhouse gases from municipal boiler plants.

*The subject of the research***:** the method of rational implementation of energy-efficient and environmental protection technologies in the field of heat supply.

The purpose of the work**:** increasing the environmental safety of urban areas by using the method of rational implementation of energy-efficient and environmental protection technologies at utility facilities that produce and consume thermal energy.

The tasks of the work *are:*

1) analysis and systematization of modern energy-efficient and ecological technologies in the field of urban heat supply;

2) formation of theoretical foundations for ensuring sustainable development of municipal energy;

3) development of an improved method of rational introduction of energy-saving technologies at objects that consume and produce thermal energy.;

4) analysis of international experience of state regulation in the field of heat supply;

5) systematization of technologies for ecological and energy modernization of building heating systems;

6) verification of the method for rational implementation of energy-saving technologies at a real facility - a building of an educational institution;

7) development of recommendations for using the results of the conducted research in solving municipal energy problems

The first chapter of the dissertation provides a comprehensive analysis of environmental problems, energy-saving and environmental technologies in the field of heat supply, which made it possible to assess the current state and trends in the development of centralized heat supply in different countries of the world, to systematize technologies for increasing the energy and environmental efficiency of municipal energy systems, and to substantiate the feasibility of implementing the principle of rational implementation of energy-efficient measures and technologies.

The second chapter analyzes and systematizes the conceptual foundations of increasing the energy and environmental safety of municipal energy, which include: the basic principles of the theory of sustainable development, the principles of the recycling economy, the concept of energy modernization of urban heating networks. The theoretical and applied foundations of using an improved method for the rational implementation of energy-saving technologies in technical systems "producer-consumer of thermal energy" are also presented. The main provisions of the scientific novelty of the dissertation research are set out.

The third chapter presents a comprehensive analysis of current trends in the modernization of the sphere of state management of municipal energy in the following areas: progressive international experience in increasing the efficiency of state regulation of urban energy systems; comparative analysis of the principles of regulation and development of municipal energy in European and Asian countries, measures to increase the efficiency of state regulation in the field of heat supply.

The fourth chapter presents the results of a complex of theoretical and experimental studies of the effectiveness of technologies for environmental and energy modernization of building heating systems, which are: systematized technologies for cleaning exhaust gases of boiler plants and energy saving technologies for facilities that consume and produce thermal energy; results of verification and assessment of the effectiveness of an improved method for the rational implementation of energy-saving technologies at a real facility - a sports facility of an educational institution.

The fifth chapter presents recommendations and proposals for the practical use of the results of the research in solving municipal energy and environmental problems by applying the following measures: practical implementation of an improved method for the rational implementation of energy-saving technologies, measures to reduce pollution of urban areas with harmful emissions from boiler plants, increasing the rational use of energy and fuel resources, and increasing the economic efficiency of municipal heat supply systems.

The scientific novelty of the obtained results, which are submitted for defense, is as follows.

1. For the first time, the feasibility of using and developing an information map form for multi-criteria assessment of the effectiveness of various strategies for the rational implementation of environmental energy-saving technologies based on the criteria of the specific cost of achieved environmental, economic and generalized effects has been scientifically substantiated, which constitutes an information basis for making reasoned technical decisions regarding the choice of the most cost-effective procedures for realizing the energy-saving potential of buildings and heat supply systems.

2. The method of rational implementation of energy-saving technologies in the field of heat supply has been improved by introducing new ecological and economic criteria for assessing the effectiveness of energy modernization procedures for technical systems "producer-consumer of thermal energy", the introduction of which allows for a more complete assessment of the degree of rationality of the use of investment resources when carrying out energy-efficient measures and implementing programs to improve the energy and environmental security of urbanized areas.

3. A mathematical model for determining the parameters and assessing the effectiveness of procedures for the rational implementation of energy-saving technologies was further developed, which took into account the losses of the integral energy-saving potential of objects that produce and consume thermal energy in the initial and final periods of its phased implementation; this allows increasing the accuracy of this mathematical model and the reliability of the environmental and economic effects established on its basis.

The practical significance of the obtained results, which are submitted to the defense, is as follows.

1. A comprehensive analysis of environmental problems, environmental protection and energy-saving technologies in the field of heat supply was conducted, which made it possible to assess the current state and trends in the development of centralized heat supply in different countries of the world, to systematize technologies for increasing the energy and environmental efficiency of municipal energy systems, and to substantiate the feasibility of implementing the principle of rational implementation of energy-efficient measures and technologies.

2. The main provisions of the theory of sustainable development, the principles of the economy of secondary processing, the concept of energy modernization of urban heating networks are systematized, and the feasibility of rational implementation of energy-saving and environmental protection measures in the field of heat supply is substantiated, an improved method for the rational implementation of energy-saving technologies is proposed.

3. The progressive international experience of state regulation of urban heat supply systems, measures to increase the efficiency of state regulation in this area were studied, and a comparative analysis of the principles of regulation and development of municipal energy in European and Asian countries was conducted.

4. The technologies for ecological and energy modernization of heating systems have been systematized: technologies for cleaning exhaust gases from boiler plants and energy saving technologies for facilities that consume and produce thermal energy; the method for rational implementation of energy-efficient technologies at a real object-a sports facility of an educational institution-has been verified.

5. Recommendations and proposals have been developed for using research results to solve municipal energy problems through: practical application of the RIEST method, reducing pollution of urbanized areas with harmful emissions from boiler plants, increasing the rational use of energy and fuel resources, and increasing the economic efficiency of heat supply systems.

6. The improved RIEST method was verified, during which its practical suitability for choosing the most investment-attractive strategy for increasing the

environmental and economic efficiency of the studied educational facility-the sports complex of Vinnytsia National Technical University – was confirmed. The studies demonstrated the possibility of increasing the energy efficiency of the research object by 67% as a result of the implementation of 5 recommended energy-saving technologies when implementing the strategy selected on the basis of the RIEST method, which provides a significant reduction in the investment resources required for this-from 88.3 ths. EUR to 69.1 ths. EUR, i.e. by 21.7%. At the same time, the following annual environmental and economic effects are achieved: reduction in thermal energy consumption – 260 MWh, fuel savings – 35.3 ths. m^3 of natural gas, reduction in atmospheric CO_2 and NOx emissions – 18.7 tons and 116.4 kg, respectively, the economic effect – 16.5 ths. EUR.

7. Based on the results of the conducted research, recommendations have been developed to increase the versatility and expand the scope of application of the improved RIEST method in technical systems "producer-consumer of thermal energy" and their elements of annual types, which include: objects that consume thermal energy-public and industrial buildings and groups of buildings, objects that transport thermal energy - heat networks of centralized and autonomous heat supply systems, objects that produce thermal energy-boiler plants, alternative and renewable energy sources, namely: high-efficiency gas boilers, heat pumps, solar systems, etc. The recommendations take into account the motivation of the owners of the studied buildings and heat supply systems and investors who ensure the implementation of the energy modernization strategy of these facilities.

The results of dissertation research have been implemented in the educational processes of student training process in Vinnytsia National Technical University, who study in specialties 101 – "ecology" and 183 - "environmental protection technologies" and the production activities of the private enterprise "INTEREKO", which is confirmed by the relevant acts of implementation.

Key words: urbanized areas, field of heat supply, environmental safety, energy-efficient technologies, environmental protection technologies, method of rational implementation.

АНОТАЦІЯ

Чжан Ле. Підвищення екологічної безпеки урбанізованих територій шляхом раціонального впровадження енергоефективних та природоохоронних технологій у сфері теплопостачання. – Кваліфікаційна наукова праця на правах рукопису.

Дисертація на здобуття наукового ступеня доктора філософії за спеціальністю 183 – «Технології захисту навколишнього середовища» (галузь знань 18 – «Виробництво та технології»). – Вінницький національний технічний університет, Вінниця, 2025.

Разом з прискоренням глобальної урбанізації, проблеми споживання енергії в містах та навколишнього середовища стають дедалі більш помітними. Як важлива частина міської інфраструктури, енергоефективність та екологічність системи опалення безпосередньо пов'язані зі сталим розвитком міста. Згідно зі статистикою, на сектор теплопостачання припадає близько 30% світового споживання енергії, також ця сфера є одним з основних джерел забруднення атмосфери такими шкідливими речовинами, як SO_2, NO_x, тверді частинки та ін. Тому питання розумного впровадження енергозберігаючих та екологічно чистих технологій та енерго-екологічної оптимізації системи опалення стало предметом значної уваги сучасних академічних та політичних кіл.

Значний негативний вплив систем комунальної енергетики на навколишнє середовище сприяє розвитку та посиленню локальних і глобальних екологічних проблем, особливо на урбанізованих територіях. Робота котельних установок і теплоелектроцентралей потребує їхнього забезпечення паливом, потреба в якому з розширенням теплових мереж зростає. У зв’язку з цим проблема підвищення еколого-енергетичної ефективності комунальної енергетики в умовах збільшення її впливу на природне середовище і урбанізовані території та зростання цін на енергоносії має високу актуальність.

Новий підхід у вирішенні цієї проблеми, який застосований у дисертаційній роботі, полягає у об’єднанні виробника, постачальника і споживача теплової енергії в єдиний технічний комплекс для якого здійснюється пошук оптимальних технічних рішень з підвищення його екологічної, ресурсної і економічної ефективності при

мінімальними інвестиційних витратах. Досягнення такого результату забезпечується раціональним впровадженням енергоощадних технологій.

В дисертації поставлено та вирішено актуальну науково-прикладну задачу підвищення ефективності екологізації систем муніципальної енергетики та поліпшення екологічного стану урбанізованих територій шляхом створення та верифікації удосконаленого методу раціонального впровадження енергоощадних технологій (РВЕТ) на об’єктах, що споживають та виробляють теплову енергію в комунальній сфері.

Проблема, вирішенню якої присвячено дисертацію: зменшення негативного впливу міських систем теплопостачання на екологічний стан урбанізованих територій.

Об’єкт дослідження: процеси забруднення довкілля викидами шкідливих речовин та парникових газів комунальних котельних установок.

Предмет дослідження: метод раціонального впровадження енергоефективних та природоохоронних технологій у сфері теплопостачання.

***Мета роботи*:** підвищення екологічної безпеки урбанізованих територій шляхом використання методу раціонального впровадження енергоефективних та природоохоронних технологій на об’єктах комунального господарства, які виробляють та споживають теплову енергію.

Завдання роботи:

1) аналіз та систематизація сучасних енергоефективних та екологічних технологій у галузі теплопостачання міст;

2) формування теоретичних основ забезпечення сталого розвитку муніципальної енергетики;

3) розробка вдосконаленого методу раціонального впровадження енергоощадних технологій на об'єктах споживачах і виробниках теплової енергії;

4) аналіз міжнародного досвіду державного регулювання у сфері теплопостачання;

5) систематизація технологій еколого-енергетичної модернізації систем опалення будівель;

6) верифікація методу раціонального впровадження енергоощадних технологій на реальному об'єкті – будівлі освітнього закладу;

7) розробка рекомендацій щодо використання результатів проведених досліджень у вирішенні проблем муніципальної енергетики.

В першому розділі дисертації проведено комплексний аналіз екологічних проблем, природоохоронних та енергозберігаючих технологій у сфері теплопостачання, що дозволило оцінити сучасний стан та тенденції розвитку централізованого теплопостачання в різних країнах світу, систематизувати технології підвищення енергетичної та екологічної ефективності муніципальних енергетичних систем, а також обґрунтувати доцільність реалізації принципу раціонального впровадження енергоефективних заходів та технологій.

В другому розділі проаналізовано та систематизовано концептуальні основи підвищення енерго-екологічної безпеки комунальної енергетики, які складають: основні положення теорії сталого розвитку, принципи економіки вторинної переробки, концепція енергетичної модернізації міських теплових мереж. Також представлено теоретичні та прикладні основи використання удосконаленого методу раціонального впровадження енергозберігаючих технологій в технічних системах «виробник-споживач теплової енергії». Викладено основні положення наукової новизни дисертаційного дослідження.

У третьому розділі проведено комплексний аналіз сучасних тенденцій модернізації сфери державного управління муніципальною енергетикою за наступними напрямами: прогресивний міжнародний досвід підвищення ефективності державного регулювання міськими енергосистемами; порівняльний аналіз принципів регулювання та розвитку муніципальної енергетики в країнах Європи та Азії, заходи підвищення ефективності державного регулювання у сфері теплопостачання.

У четвертому розділі представлені результати проведення комплексу теоретичних та експериментальних досліджень ефективності технологій екологічної та енергетичної модернізації систем опалення будівель якими є: систематизовані технології очищення відпрацьованих газів котельних установок та технології енергозбереження для об'єктів, які споживають та виробляють теплову енергію; результати верифікації та оцінки ефективності удосконаленого методу раціонального впровадження енергоощадних технологій на реальному об'єкті – спортивній споруді навчального закладу.

У п’ятому розділі представлені рекомендації та пропозиції щодо практичного використання результатів проведених досліджень у вирішенні муніципальних енерго-екологічних проблем шляхом застосування таких заходів: практичної реалізації удосконаленого методу раціонального впровадження енергоощадних технологій, заходів щодо зменшення забруднення урбанізованих територій шкідливими викидами котельних установок, підвищення раціональності використання енергетичних та паливних ресурсів, а також підвищення економічної ефективності муніципальних систем теплопостачання.

Наукова новизна отриманих результатів, що виносяться на захист, полягає в наступному:

1. *Вперше* науково обґрунтовано доцільність використання та розроблено форму інформаційної карти для багатокритеріальної оцінки ефективності різних стратегій раціонального впровадження природоохоронних енергоощадних технологій на основі критеріїв питомої собівартості досягнутих екологічних, економічних та узагальненого ефектів, яка складає інформаційну основу для прийняття аргументованих технічних рішень щодо вибору найбільш рентабельних процедур реалізації потенціалу енергозбереження будівель та систем теплопостачання.

2. *Удосконалено* метод раціонального впровадження енергоощадних технологій в сфері теплопостачання шляхом введення нових еколого-економічних критеріїв оцінки ефективності процедур енергомодернізації технічних систем «виробник-споживач теплової енергії», введення яких дозволяє більш повноцінно оцінювати ступінь раціональності використання інвестиційних ресурсів при проведенні енергоефективних заходів та реалізації програм підвищення енерго-екологічної безпеки урбанізованих територій.

3. *Дістала подальшого розвитку* математична модель для визначення параметрів та оцінки ефективності процедур раціонального впровадження енергоощадних технологій, в якій були враховані втрати інтегрального потенціалу енергозбереження об’єктів, що виробляють та споживають теплову енергію на початковому та кінцевому періодах його поетапної реалізації; це дозволяє підвищити точність даної математичної моделі та достовірність встановлених на її основі екологічних та економічних ефектів.

Практичне значення отриманих результатів полягає у наступному:

1. Проведено комплексний аналіз екологічних проблем, природоохоронних та енергозберігаючих технологій в сфері теплопостачання, що дозволило оцінити сучасний стан та тенденції розвитку централізованого теплопостачання в різних країнах світу, систематизувати технології підвищення енерго-екологічної ефективності систем комунальної енергетики та обґрунтувати доцільність реалізації принципу раціонального впровадження енергоефективних заходів і технологій.

2. Систематизовано основні положення теорії сталого розвитку, принципи економіки вторинної переробки, концепції енергомодернізації міських теплових мереж та обґрунтовано доцільність раціонального впровадження енергоощадних та природоохоронних заходів в сфері теплопостачання, запропоновано вдосконалений метод раціонального впровадження енергоощадних технологій.

3. Досліджено прогресивний міжнародний досвід державного регулювання систем теплопостачання міст, заходи підвищення ефективності державного регулювання в цій сфері, проведено порівняльний аналіз принципів регулювання та розвитку муніципальної енергетики в країнах Європи і Азії.

4. Систематизовано технології еколого-енергетичної модернізації систем опалення: технологій очищення відхідних газів котельних установок та технологій енергозбереження для об'єктів, які споживають та виробляють теплову енергію; проведено вирифікацію методу раціонального впровадження енергоефективних технологій на натурному об’єкті – спортивної споруди закладу освіти.

5. Розроблено рекомендації та пропозиції щодо використання результатів досліджень у вирішення проблем муніципальної енергетики за рахунок: практичного застосування методу РВЕТ, зменшення забруднення урбанізованих територій шкідливими викидами котельних установок, підвищення раціональності використання енергетичних та паливних ресурсів, підвищення економічної ефективності систем теплопостачання.

6. Проведено верифікацію удосконаленого методу РВЕТ, в ході якої підтверджено його практичну придатність для вибору найбільш інвестиційно привабливої стратегії підвищення еколого-економічної ефективності

досліджуваного об'єкту сфери освіти – спортивного комплексу Вінницького національного технічного університету. Дослідження продемонстрували можливість підвищення енергоефективності об'єкту досліджень на 67 % в результаті впровадження 5-ри рекомендованих енергоощадних технологій при реалізації обраної на основі методу РВЕТ стратегії, яка забезпечує суттєве зменшення потрібних для цього витрат інвестиційних ресурсів – з 88,3 тис. EUR до 69,1 тис. EUR, тобто на 21,7%. При цьому досягаються такі річні еколого-економічні ефекти: зменшення витрат теплової енергії – 260 МВт·год, економія палива – 35,3 тис. $м^3$ природнього газу, зменшення викидів у атмосферу CO_2 і NOx – 18,7 т і 116,4 кг, відповідно, економічний ефект – 16,5 тис. EUR.

7. На основі результатів проведених досліджень розроблено рекомендації щодо підвищення універсальності та розширення сфери застосування удосконаленого методу РВЕТ в технічних системах «виробник-споживач теплової енергії» та їх елементах річних типів, до яких відносяться: об'єкти, що споживають теплову енергію – громадські та промислові будівлі та групи будівель, об'єкти, що транспортують теплову енергію – теплові мережі централізованих та автономних систем теплопостачання, об'єкти, що виробляють теплову енергію – котельні установки, альтернативні та відновлювальні джерела енергії, а саме: газові котли підвищеної ефективності, теплові насоси, геліосистеми, тощо. В рекомендаціях враховано мотивацію власників досліджуваних будівель та систем теплопостачання та інвесторів, що забезпечують реалізацію стратегії енергомодернізації даних об'єктів.

Результати дисертаційних досліджень впроваджено в навчальні процеси підготовки студентів Вінницького національного технічного університету, які навчаються за спеціальностями 101 – «Екологія» і 183 – «Технології захисту навколишнього середовища» та виробничу діяльність приватного підприємства «ІНТЕРЕКО», що підтверджується відповідними актами впровадження.

Ключові слова: урбанізовані території, сфера теплопостачання, екологічна безпека, енергоефективні технології, технології захисту навколишнього середовища, метод раціонального впровадження.

LIST OF THE APPLICANT'S PUBLICATIONS BY DISSERTATION TOPIC

Articles in periodical scientific publications indexed in the Scopus database:

1. **Zhang Le**, Polyvianchuk Andrii. Development of coal flue gases denitrification technologies in China. *Environmental problems*. Vol. 10, No. 1, 2025. – P. 88-96. DOI: https://doi.org/10.23939/ep2025.01.088.

(The applicant has made a detailed analysis and comparison of common coal-fired flue gas denitrification technologies).

2. **Zhang Le**, Polyvianchuk Andrii. Application of denitration technology in flue gas treatment of coal-fired boiler. *Environmental problems*. Vol. 10, No. 2, 2025. – P. 88-96. DOI: https://doi.org/10.23939/ep2025.02.110.

(The applicant compared and analyzed the current status of two denitrification technologies in coal-fired boiler flue gas treatment, and pointed out the existing problems)

Articles in professional publications of Ukraine, category «Б»:

3. **Чжан Ле**, Полив'янчук А.П. «Очищення димових газів вугільних котлів від оксидів азоту. аналіз проблем та перспектив». *Вісник ВПІ*, вип. 2, с. 39–44, Квіт. 2025. DOI: https://doi.org/10.31649/1997-9266-2025-179-2-39-44.

(The applicant studied and analyzed the four common denitrification technologies in flue gas emissions from heating boilers).

Individual collective monographs

4. **Zhang Le**. Analysis of world experience in state regulation and reform of the thermal power industry. Technical, agricultural and applied sciences as mechanisms for the development of human self-knowledge: collective monograph. *International Science Group*, Boston. 2024. – P. 368-383. ISBN: 979-8-89480-692-1. DOI:

https://doi.org/10.46299/ISG.2024.MONO.TECH.4.

5. **Zhang Le**. Theoretical basics of ensuring sustainable development of urban heat supply. Global transformations of social development. *Видавництво «Новий курс»*, Харків. 2024. – P. 144-154. ISBN:978-617-7886-66-1, DOI: https://doi.org/10.61718/mon, URL: https://www.newroute.org.ua/wp-content/uploads/2024/11/globtran.pdf.

Co-authored collective monograph

6. **Zhang Le**, Polyvianchuk Andrii. Analysis of energy-efficient and environmental technologies in the field of heat supply. Science, technology and innovation in the context of global transformation: Scientific monograph. *Baltija Publishing*, Riga. 2024. – P. 96-121. ISBN: 78-9934-26-499-3. DOI: https://doi.org/10.30525/978-9934-26-499-3-5.

(The applicant conducted a comprehensive analysis of energy-saving and environmentally friendly technologies in the field of heat supply).

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(The applicant systematically analyzed the main types of pollutants emitted during boiler operation and their causes, and proposed specific energy-saving and environmental protection measures and improvement plans).

8. Polyvianchuk Andrii, **Zhang Le**. Analysis of the current state and

development prospects of urban central heating in China. *Proceedings of the X International Scientific and Practical Conference «Modern methods of applying scientific theories»*, Lisbon, Portugal, March 14-17, 2023, P. 433-436, ISBN: 979-8-88896-520-7. URL: https://isg-konf.com/modern-methods-of-applying-scientific-theories.

(The applicant analyzed the current situation and problems of centralized heating in Chinese cities).

9. Polyvianchuk Andrii, **Zhang Le**. Increasing the energy efficiency of buildings with household and centralized HVAC systems by using ground heat pumps. *Proceedings of the XXVI International Scientific and Practical Conference «Scientific trends and ways of solving modern problems»*, La Rochelle, France, July 04-07, 2023, P. 233-235, ISBN: 979-8-89074-572-9. URL: https://isg-konf.com/scientific-trends-and-ways-of-solving-modern-problems.

(The applicant introduced the principles and advantages of ground source heat pump technology in detail).

10. **Zhang Le**, Polyvianchuk Andrii. Influencing factors and energy-saving technology of heating boiler. *9th International Environmental Conference II: International Scientific and Practical Symposium on Decarbonization, Post-Mining and Energy Efficiency Infrastructure of Ukraine*, Vinnytsia: Vinnytsia National Technical University, September 25-27, 2024. P. 370-372, ISBN 978-617-8163-22-8. URL: https://press.vntu.edu.ua/index.php/vntu/catalog/book/854.

(The applicant analyzed the factors that affect the energy efficiency of heating boilers).

CONTENTS

LIST OF ABBREVIATIONS AND CONVENTIONAL NOTATIONS

Basic abbreviations

EST – energy-saving technologies;

RIEST – rational implementation of energy-saving technologies;

RO – research object.

Parameters of the current energy, ecological and economic state of the RO

S_{ha} – total heated area of the building, m^2;

Q – annual thermal energy requirement of the building, Wh;

Q_S – specific annual thermal energy demand of a building, Wh/m^2;

V_{fuel} – annual fuel (natural gas) requirement of the RO, m^3;

M_{pol} – annual mass emission of harmful pollutants into the atmosphere, kg;

C – annual economic costs for heat supply of the, EUR;

List of ETs recommended for implementation

TM (r) – thermal modernization of the roof;

TM (vs) – thermal modernization of the ventilation system;

TM (w) – thermal modernization of walls;

SH – smart home technology;

HS – alternative source of thermal energy – heliosystem;

Annual effects from the introduction of EST

ΔQ – energy saving effect: thermal energy savings, Wh;

ΔQ_S – specific energy saving effect, Wh/ m^2;

ΔV_{fuel} – resource-saving effect: saving fuel (natural gas), m^3;

ΔM_{pol} – reduction of harmful pollutant emissions, kg;

ΔC – saving of economic costs for heat supply of buildings, EUR;

ΔP – dimensionless generalized ecological and economic effect, %;

Indicators of the specific value of the achieved ecological and economic effects

Δq – specific cost of energy saving effect, EUR/Wh;

Δv_{fuel} – specific cost of resource-saving effect, EUR/m^3;

Δm_{pol} – specific cost of ecological effect, EUR/kg;

Δc – specific cost of economic effect, EUR/EUR;

Δp – specific cost of the generalized ecological and economic effect, EUR/%.

Stages of EST implementation strategies and their parameters

Stage A – the first quick-payback stage with a payback period of up to 4 years;

Stage B – the second medium-payback stage with a payback period of 4 to 8 years;

Stage C – the third long-term payback stage with a payback period of 8 to 12 years;

ΔC_A, ΔC_B, ΔC_C – economic effects of stages A, B and C, EUR;

T_{ppA}, T_{ppB}, T_{ppC} – payback periods of stages A, B and C, years;

$F_{in(est)A}$, $F_{in(est)B}$, $F_{in(est)C}$ – estimated costs of stages A, B and C, EUR;

$F_{in(act)A}$, $F_{in(act)B}$, $F_{in(act)C}$ – actual costs of stages A, B and C, EUR;

ΔT_A, ΔT_B, ΔT_C – delay periods for the start of stages A, B and C, years;

Parameters of EST implementation strategies

T_{pp1}, T_{ppX} – payback periods of the 1st and Xth strategies, years;

ΔT_{ppX} – increase in the payback period of the Xth strategy compared to the 1st strategy, years;

$F_{in(est)1}$, $F_{in(est)X}$ – estimated costs of the 1st and Xth strategies, EUR;

$F_{in(act)1}$, $F_{in(act)X}$ – actual costs of the 1st and Xth strategies, EUR;

F_{lost} – excessive financial costs for heating the RO, EUR;

F_{save} – saved financial resources from the implementation of EST, EUR;

ΔF – self-financing resource of the RO, EUR;

δF – relative saving of investment costs, %.

INTRODUCTION

Rationale for choosing a research topic

With the acceleration of global urbanization, the problems of energy consumption in cities and the environment are becoming increasingly prominent. As an important part of urban infrastructure, the energy efficiency and environmental friendliness of the heating system are directly related to the sustainable development of the city. According to statistics, the thermal energy sector accounts for about 30% of global energy consumption, and this area is also one of the main sources of atmospheric pollution with harmful substances such as SO_2, NO_x, particulate matter, etc. Therefore, the issue of rational implementation of energy-saving and environmentally friendly technologies and energy-environmental optimization of the heating system has become the subject of considerable attention of modern academic and political circles.

When addressing this issue, it should also be taken into account the fact that in the process of urbanization and expansion of urban heat supply systems, traditional heating technologies in many countries continue to be based on coal-fired boiler houses, which have low energy efficiency and significantly pollute the atmosphere with emissions of pollutants. For example, in northern China, during the winter heating season, SO_2 and NO_x emissions from coal-fired boilers account for more than 40% of the total annual pollutant emissions. This not only exacerbates environmental problems such as smog, but also poses a threat to the health of residents. In addition, the green transformation of China's thermal power industry is inevitable to achieve the goal of "dual carbon" - a strategy aimed at achieving peak carbon emissions by 2030 and carbon neutrality, that is, net-zero emissions, by 2060. In this context, the study of energy-saving and environmentally friendly technologies in the heating sector not only helps to reduce energy consumption and pollutant emissions, but also provides technical support for urban environmental safety, which is of great theoretical and practical significance.

From an international perspective, European countries such as Denmark and Sweden began to promote district heating and renewable energy technologies as early as the 1980s, and their successful experience has become a benchmark for the whole world. In contrast, Asian countries such as China and South Korea were late in introducing innovations in heating technologies, but in recent years, thanks to political guidance and technology introduction, they have also made significant progress. Therefore, a systematic analysis of the regulatory experience and technical paths of different countries is of important reference value for promoting the sustainable development of the heating industry in China and other countries.

On the other hand, the development of energy is related to a global problem that cannot be ignored, such as climate change. Carbon dioxide is considered one of the most important greenhouse gases causing climate change, and the increase in the use of fossil fuels is a major factor increasing global energy-related carbon dioxide emissions. In recent years, extreme weather events have frequently occurred around the world. Responding to global climate problems and reducing carbon emissions have become a must-have issue for all countries. Accelerating the promotion of energy transformation and green and low-carbon transformation has become a must-have for all countries. Countries around the world have consistently set climate targets that meet their national conditions. Thus, today, 138 UN member states have set carbon neutrality targets, and the rest have set carbon emission reduction targets.

Thus, the significant negative impact of municipal energy systems on the environment contributes to the development and exacerbation of local and global environmental problems, especially in urban areas. Operation of boiler houses and thermal power plants requires their provision with fuel, the need for which is growing with the expansion of heating networks. In this regard, the problem of increasing the environmental and energy efficiency of municipal energy in the context of its growing impact on the natural environment and urbanized areas and rising energy prices is very relevant.

A new approach to solving this problem, which is used in the dissertation, is to combine the producer, supplier and consumer of thermal energy into a single technical complex for which the search for optimal technical solutions to increase its environmental, resource and economic efficiency with minimal investment costs is carried out. Achieving such a result is ensured by the rational implementation of energy-saving technologies.

The dissertation sets and solves the current scientific and applied task of increasing the efficiency of greening municipal energy systems and improving the ecological state of urbanized areas by creating and verifying an improved method for the rational implementation of energy-saving technologies at objects that consume and produce thermal energy in the municipal sector.

Connection of work with scientific programs, plans, topics

The work was carried out in accordance with the research topics of the Department of Ecology, Chemistry and Environmental Protection Technologies of Vinnytsia National Technical University. The research results were used in the implementation of state-funded scientific and research works: “Improving the ecological and energy security of urbanized areas through phased rational implementation of energy-efficient measures in the field of heat supply” (RN 0123U101998, head: professor A.P. Polyvianchuk) and “Improving the efficiency of decarbonization and greening of municipal energy by the method of optimized implementation of energy-saving technologies” (RN 0124U001473, head: professor V.G. Petruk).

The problem, the solution of which is devoted to the dissertation: reducing the negative impact of urban heat supply systems on the ecological state of urban areas.

The object of the study: processes of environmental pollution by emissions of harmful substances and greenhouse gases from municipal boiler plants.

The subject of the research: the method of rational implementation of energy-efficient and environmental protection technologies in the field of heat supply.

The purpose and tasks of the research

The purpose of the work: increasing the environmental safety of urban areas by using the method of rational implementation of energy-efficient and environmental protection technologies at utility facilities that produce and consume thermal energy.

The tasks of the work are: 1) analysis and systematization of modern energy-efficient and ecological technologies in the field of urban heat supply; 2) formation of theoretical foundations for ensuring sustainable development of municipal energy; 3) development of an improved method of rational introduction of energy-saving technologies at objects that consume and produce thermal energy; 4) analysis of international experience of state regulation in the field of heat supply; 5) systematization of technologies for ecological and energy modernization of building heating systems; 6) verification of the method for rational implementation of energy-saving technologies at a real facility - a building of an educational institution; 7) development of recommendations for using the results of the conducted research in solving municipal energy problems.

Research methods. When solving the problems of the dissertation work, the following methods were used: *analysis, systematization and generalization of information* - when studying modern energy-efficient and environmental technologies in the field of urban heat supply, studying international experience of state regulation in the field of heat supply; *mathematical modeling* - when creating the theoretical foundations of an improved method for the rational implementation of energy-saving technologies (RIEST); *calculation experiment* - when testing the RIEST method on a real object; experimental research - when conducting instrumental control of the heat-technical parameters of the studied real object - the building of an educational institution; *experimental planning* - when verifying the RIEST method and *statistical data processing* - when assessing the adequacy of the created mathematical models.

Scientific novelty of the obtained results

1. *For the first time*, the feasibility of using and developing an information map form for multi-criteria assessment of the effectiveness of various strategies for the rational implementation of environmental energy-saving technologies based on the criteria of the specific cost of achieved environmental, economic and generalized effects has been *scientifically substantiated*, which constitutes an information basis for making reasoned technical decisions regarding the choice of the most cost-effective procedures for realizing the energy-saving potential of buildings and heat supply systems.

2. The method of rational implementation of energy-saving technologies in the field of heat supply *has been improved* by introducing new ecological and economic criteria for assessing the effectiveness of energy modernization procedures for technical systems "producer-consumer of thermal energy", the introduction of which

allows for a more complete assessment of the degree of rationality of the use of investment resources when carrying out energy-efficient measures and implementing programs to improve the energy and environmental security of urbanized areas.

3. A mathematical model for determining the parameters and assessing the effectiveness of procedures for the rational implementation of energy-saving technologies *was further developed*, which took into account the losses of the integral energy-saving potential of objects that produce and consume thermal energy in the initial and final periods of its phased implementation; this allows increasing the accuracy of this mathematical model and the reliability of the environmental and economic effects established on its basis.

Practical significance of the obtained results

1. A comprehensive analysis of environmental problems, environmental protection and energy-saving technologies in the field of heat supply was conducted, which made it possible to assess the current state and trends in the development of centralized heat supply in different countries of the world, to systematize technologies for increasing the energy and environmental efficiency of municipal energy systems, and to substantiate the feasibility of implementing the principle of rational implementation of energy-efficient measures and technologies.

2. The main provisions of the theory of sustainable development, the principles of the economy of secondary processing, the concept of energy modernization of urban heating networks are systematized, and the feasibility of rational implementation of energy-saving and environmental protection measures in the field of heat supply is substantiated, an improved method for the rational implementation of energy-saving technologies is proposed.

3. The progressive international experience of state regulation of urban heat supply systems, measures to increase the efficiency of state regulation in this area were studied, and a comparative analysis of the principles of regulation and development of municipal energy in European and Asian countries was conducted.

4. The technologies for ecological and energy modernization of heating systems have been systematized: technologies for cleaning exhaust gases from boiler plants and energy saving technologies for facilities that consume and produce thermal energy; the

method for rational implementation of energy-efficient technologies at a real object-a sports facility of an educational institution-has been verified.

5. Recommendations and proposals have been developed for using research results to solve municipal energy problems through: practical application of the RIEST method, reducing pollution of urbanized areas with harmful emissions from boiler plants, increasing the rational use of energy and fuel resources, and increasing the economic efficiency of heat supply systems.

6. The improved RIEST method was verified, during which its practical suitability for choosing the most investment-attractive strategy for increasing the environmental and economic efficiency of the studied educational facility-the sports complex of Vinnytsia National Technical University – was confirmed. The studies demonstrated the possibility of increasing the energy efficiency of the research object by 67% as a result of the implementation of 5 recommended energy-saving technologies when implementing the strategy selected on the basis of the RIEST method, which provides a significant reduction in the investment resources required for this-from 88.3 ths. EUR to 69.1 ths. EUR, i.e. by 21.7%. At the same time, the following annual environmental and economic effects are achieved: reduction in thermal energy consumption – 260 MWh, fuel savings – 35.3 ths. m^3 of natural gas, reduction in atmospheric CO_2 and NOx emissions – 18.7 tons and 116.4 kg, respectively, the economic effect – 16.5 ths. EUR.

7. Based on the results of the conducted research, recommendations have been developed to increase the versatility and expand the scope of application of the improved RIEST method in technical systems "producer-consumer of thermal energy" and their elements of annual types, which include: objects that consume thermal energy-public and industrial buildings and groups of buildings, objects that transport thermal energy - heat networks of centralized and autonomous heat supply systems, objects that produce thermal energy-boiler plants, alternative and renewable energy sources, namely: high-efficiency gas boilers, heat pumps, solar systems, etc. The recommendations take into account the motivation of the owners of the studied buildings and heat supply systems and investors who ensure the implementation of the

energy modernization strategy of these facilities.

8. The results of dissertation research have been implemented in the educational processes of student training process in Vinnytsia National Technical University, who study in specialties 101 – "ecology" and 183 – "environmental protection technologies" and the production activities of the private enterprise "INTEREKO", which is confirmed by the relevant acts of implementation.

Personal contribution of the applicant

All scientific provisions and results of the dissertation submitted for defense were obtained by the applicant independently. According to the list of the applicant's published works on the topic of the dissertation, his personal contribution to the research results is as follows: in work [1] - a detailed analysis and comparison of common technologies for denitrification of flue gases operating on coal; in work [2] - a comparative analysis of the current state of two denitrification technologies in the purification of flue gases of coal-fired boilers; in work [3] - the effectiveness of the method of rational implementation of energy-saving technologies in the studied building was investigated and analyzed; in work [4] - four common technologies for denitrification in flue gas emissions from heating boilers were investigated and analyzed; in work [5] - problems of operation of the city's centralized heating systems were analyzed; in work [6] - an analysis of the world experience of state regulation and reform of the heat and power industry was conducted; in work [7] - an analysis and systematization of the theoretical foundations for ensuring the sustainable development of urban heat supply; in work [8] - a comprehensive analysis of energy-saving and environmentally friendly technologies in the field of heat supply was conducted; in work [9] - the main types of pollutants emitted during boiler operation and their causes are analyzed, and specific measures and improvement plans for energy conservation and environmental protection are proposed; in work [10] - the current situation and problems of centralized heating in Chinese cities are analyzed; in work [11] - the principles and advantages of geothermal heat pump technologies are analyzed in detail; in work [12] - the factors affecting the energy efficiency of heating boilers are analyzed.

Publications. The main results of the dissertation research were published in 10 scientific works, including: 2 articles in periodicals indexed in the Scopus scientometric database; 1 articles in professional publications of Ukraine, category "B"; 2 individual collective monographs; 1 collective monograph in co-authorship and 4 scientific works of an approbatory nature - materials of international scientific and practical conferences.

Approbation of work results

The main content of the dissertation and its provisions were presented and discussed at scientific and practical conferences and forums of various levels:

1. Proceedings of the V International Scientific and Practical Conference «Prospects of modern science and education», Stockholm, Sweden, February 7-10, 2023.

2. Proceedings of the X International Scientific and Practical Conference «Modern methods of applying scientific theories», Lisbon, Portugal, March 14-17, 2023.

3. Proceedings of the XXVI International Scientific and Practical Conference «Scientific trends and ways of solving modern problems», La Rochelle, France, July 04-07, 2023.

4. 9th International Environmental Conference II: International Scientific and Practical Symposium on Decarbonization, Post-Mining and Energy Efficiency Infrastructure of Ukraine, Scientific Works Collection, Ukraine, Vinnytsia: Vinnytsia National Technical University, September 25-27, 2024.

Structure and scope of the thesis.

The dissertation consists of 257 pages of printed text, consisting of an introduction, 5 chapters, a general conclusion, a list of used sources, and 3 appendices. The work is illustrated with 13 tables and 24 figures, 3 figures and 1 table occupy full pages. The main part of the dissertation consists of 190 pages of printed text. The list of used sources contains 168 titles.

CHAPTER 1 ANALYSIS OF ENERGY-EFFICIENT AND ECOLOGICAL TECHNOLOGIES IN THE HEAT SUPPLY INDUSTRY

The world is experiencing climate change, environmental degradation, and resource shortages. With the rapid economic growth in recent years, all aspects of people's lives have been upgraded and improved to a certain extent. However, some environmental and energy-related problems have become increasingly serious. We need to pay more attention to energy shortages and environmental pollution. We must first consider how to save energy and make full use of energy [1].

In some cold areas, the heating method used is mainly traditional combustion boilers for heating, but this heating method has a large degree of pollution to the ecological environment. When used, it often produces a large amount of waste gas and smoke. Although these waste gas and smoke diffuse slowly in the winter when the temperature is low, the degree of pollution is still relatively large. The flue gas pollution of heating boilers has become an important part of governance at this stage. In addition, although the heating method of using centralized heating boilers has certain economic benefits in application, it often consumes a lot of resources and may also cause serious damage to the environment. The combustion of coal in heating boilers will produce flue gas, which usually contains many pollutants, such as nitrogen oxides, sulfur oxides, etc., which not only damage the urban environment, but also threaten people's health.

With the extensive use of natural gas, natural gas cogeneration and gas boiler heating have become an important urban heating method. The heat released by the combustion of natural gas in the boiler will not be fully used, and some losses will inevitably occur. Among them, smoke exhaust loss is the largest of all heat losses. If the heat in the flue gas emissions is recycled and utilized, the thermal efficiency of the boiler can be improved, which is of great significance to energy conservation and environmental protection. In addition, the emission of nitrogen oxides in gas boilers has attracted great attention. Through the application research and analysis of the deep utilization of flue gas waste heat and the integrated denitrification technology, the advantages of this technology over conventional solutions in energy saving and environmental protection benefits are obtained. Finally, a conclusion is drawn on how to transform and apply the flue gas waste heat utilization technology to the heating gas boiler.

1.1 Analysis of the problem of pollution of cities by energy facilities

Human beings and the environment are inseparable. The environment provides renewable energy and non-renewable energy as the basic supply for various human activities. The corresponding various human activities have caused certain energy waste and consumption, which has damaged the natural environment to a certain extent and caused certain pollution. While using energy, the environment and pollution control have been changed to a certain extent. All of these constitute a dynamic model between environment, energy and pollution control.

According to the pollutant emission data of various industries listed in the references [2] "Pollutants and Greenhouse Gases Emitted into the Atmosphere by Stationary Pollution Sources in 2020" [3] of the State Statistics Service of Ukraine and "China's Ecological Environment Bulletin 2023" [4] of the Ministry of Ecology and

Environment of China, the main sources of air pollution in Ukraine and China can be divided into mining, processing industry, energy production and other fields. Figure 1.1 shows the main air pollutants in various fields in Ukraine and China and their approximate proportions.

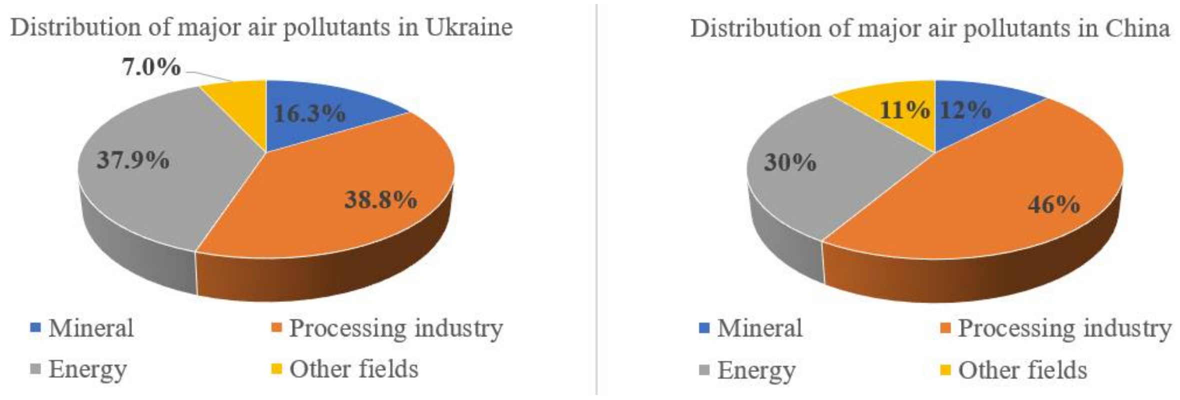

Fig. 1.1 – Major air pollutants in Ukraine and China

As can be seen from the data in the above figure, in Ukraine and China, the energy and process industries have a high proportion of pollutant emissions, indicating that these industries occupy an important position in the country's industrial structure and may lack adequate pollution control measures. Ukraine and China face similar challenges in controlling air pollution, especially in the energy and process industries. Both countries need to further strengthen environmental supervision and technological innovation to reduce pollutant emissions and improve air quality.

In terms of economic energy consumption, 25.7% of Ukraine's energy is used for building energy supply, while 74.3% is used in other economic sectors [2,3]. In China, 24% of energy is used for building energy supply and 76% is used in other economic sectors [4]. This shows that in both countries, building energy supply accounts for a quarter of economic energy consumption. Figure 1.2 shows the distribution of energy consumption in the Ukrainian and Chinese economies, which compares the energy distribution ratio between building energy supply and other economic sectors in the two countries.

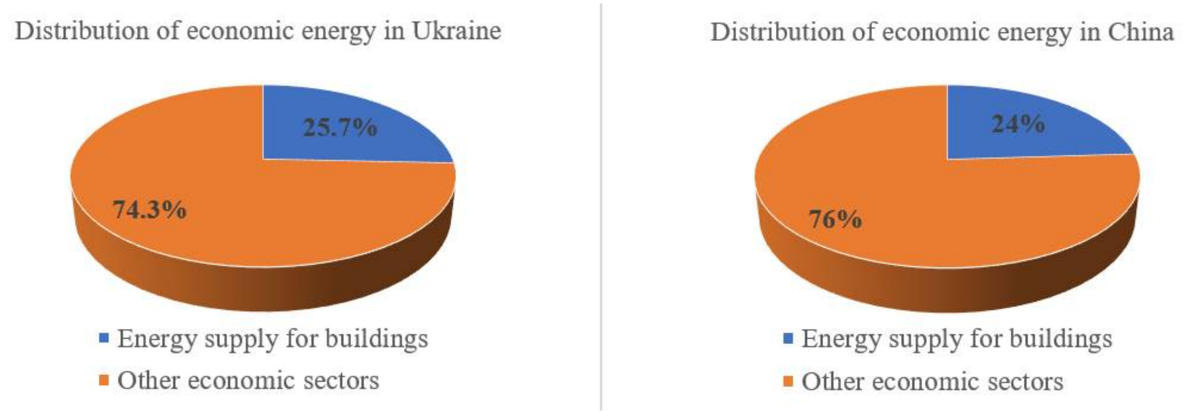

Fig. 1.2 – Distribution of economic energy in Ukraine and China

As can be seen from the data above, Ukraine and China show similar patterns in the distribution of economic energy consumption. This distribution reflects the importance of the construction sector in the economies of both countries and the potential impact of energy efficiency policies in the construction sector.

As a developing country, China's urbanization process is accelerating. The pursuit of economic development has led to environmental deterioration, increased pollution, and further reduction in the degree of urban beautification, which has brought negative impacts on the economic development of the city to a certain extent, such as investment from foreign investment companies. The environmental problems caused by, such as water pollution, air pollution, noise pollution, solid waste, etc., are huge challenges we face. Only by reasonably macro-regulating the relationship between environment, energy and pollution control can we better develop the economy, be more conducive to the beautification of human living space, and realize scientific and modern planning and management. Environment, energy and pollution control must be interdependent. Environment, energy and pollution constitute the relationship between input and output. The adverse consequences caused by unreasonable economic methods, such as resource scarcity, ecological environment changes, and climate change, have brought huge negative impacts on urban economic development. Nowadays, the losses caused by environmental impacts on rural drinking water and irrigation are huge. The industry should strengthen production management and innovate production processes. The government uses legislation and economic measures to promote industrial innovation technology, which is the most basic and effective way to prevent environmental pollution. However, the adverse effects of life and production on the environment are difficult to prevent and control fundamentally, so controlling environmental pollution is the basic task of environmental engineering.

Now environmental problems are mainly manifested in urbanization, and a reasonable urban environmental management model is necessary and urgent. Social phenomena caused by environmental problems are common, the most important of which is water pollution. Many companies produce various unqualified products at the cost of polluting the environment without meeting national standards and specifications. Pollution production and discharge far exceed the standard. These lead to energy waste and environmental pollution. For current enterprises, enterprises should focus on their own clean production, abandon the traditional end-of-pipe treatment model, and adopt the whole process of enterprise clean production to control the whole process of product life cycle, significantly reduce the amount of pollution, significantly reduce the amount of pollution, increase resource utilization, reduce resource consumption, increase product output, reduce product costs, significantly increase economic benefits, and basically no pollution transfer. Enterprise clean production is beneficial to the whole society and human habitation. However, the end-of-pipe treatment we know has a large amount of pollution, a large amount of pollution, a low resource utilization rate, an increase in resource consumption, a decrease in product output, and an increase in product costs. These are not comparable to clean production.

Environmental pollution is global, and almost all countries and cities face environmental pollution problems; although some environmental pollution occurs in one region, it will flow to other regions. The environmental system has its own unique balance. Human activities and the pollution they bring destroy the balance of the environmental system, which will have a long-term impact on the urban environment and may eventually affect the survival and development of human beings themselves. Enterprises should vigorously develop their own property rights, improve their own technical assembly level through the introduction and absorption of foreign technology, have certain development capabilities, improve the depth of resource processing and utilization, promote the use of current high-tech, and realize the clean production of enterprises. Government departments should coordinate enterprises at all levels, be responsible for the audit standards of clean production of enterprises, let the current enterprises that do not meet the regulations stop production, let the enterprises that meet the regulations grow up, and strive to coordinate the relationship between environment, energy, and pollution. The ecological environment is a non-renewable resource. Solving the pollution and energy crisis is our responsibility that cannot be slackened.

For environmental, energy, and pollution control, it is ultimately the basic element of the environment. As a carrier, the environment has a certain capacity and has a subtle influence on the current status of energy and pollution. For environmental issues, the legal means implemented by the government are also a social behavior norm. Reducing environmental pollution should comply with the relevant laws and regulations of the enterprise, and under the supervision of the government, protect the environment, do not affect the living order of surrounding residents, and use resources reasonably and fully. Economic means should be used to limit the economic efficiency brought by the environment, energy and pollution. We cannot blindly pursue the benefits brought by damaging the environment, nor can we blindly pursue the benefits brought by energy. This requires coordinating the dynamic relationship between the environment, energy and pollution during this period, and technical means, administrative means and educational means are needed to manage environmental problems in accordance with the law.

According to whether energy consumption causes environmental pollution, it can be divided into polluting energy and clean energy. Polluting energy includes coal, oil, etc., and clean energy includes hydropower, electricity, solar energy, wind energy and nuclear energy. Environment, energy and pollution control must complement each other, depend on each other and integrate each other. China is currently the second largest energy producer and consumer in the world. The continuous growth of energy supply has provided important support for economic and social development. However, the environmental problems caused, such as water pollution, air pollution, noise pollution, solid waste, etc., are huge challenges we face. Only by reasonable macro-control of the relationship between environment, energy and pollution control. Only in this way can we better develop the economy sustainably, be more conducive to the beautification of human living space, and realize scientific and modern planning and management.

1.2 Current state and trends in the development of centralized heat supply in different countries of the world

The overall goal of district heating is to achieve comprehensive satisfaction of economic benefits, environmental benefits, and social benefits. Economic, environmental, and management factors determine the development model of district heating [5]. Due to differences in geographical location, energy structure, and economic conditions, each country adopts different heating methods according to its actual situation to meet the heating needs of different users. This section introduces the development and current status of heating in the United States, Ukraine, Denmark, China, Japan, and South Korea from the aspects of energy structure and heating methods.

Development status of European and American countries. Central heating in the United States and EU countries started early, and has gone through the simple management stage, infrastructure construction stage, comprehensive development stage and automation control stage [6]. After the 1970s, countries such as Denmark, Norway, Poland and Germany began to develop multi-energy heating. Natural gas, fuel oil, garbage, bioenergy, heat pump technology, etc. were applied to urban central heating, achieving significant economic, social and environmental benefits. Developed countries in Europe and the United States focus on the development and application of intelligent control technology for central heating, and are at the leading level in the industry [7,8].

The United States is the first country in the world to use centralized heating. However, due to the vast land and sparse population of the United States and the scattered living characteristics of American families, the heating mode of families is basically decentralized. American residential and villa buildings basically use independent heating devices for each household, while apartments generally use boilers in front of the building to heat the entire apartment. According to the survey data on residential energy consumption released by the U.S. Energy Information Administration, the vast majority of American families use gas furnaces, electric furnaces or heat pumps as winter heat sources. At present, the United States mainly uses natural gas, electricity, and oil as heating fuels. According to statistics from the U.S. Energy Information Administration, natural gas heating accounts for 47%, electricity heating accounts for 40%, oil heating accounts for 5%, propane heating accounts for 5%, wood fuel heating accounts for 2%, and other energy sources account for 1%, as shown in Figure 1.3. According to the U.S. energy and climate strategy, renewable energy heating will also be an essential part of the future U.S. fuel diversification strategy [9,10].

The centralized heating technology in Ukrainian cities has developed rapidly, from the original artificial steam and lime water heating to the current heating from gas combustion. With the development of technology, Ukrainian cities are now also beginning to introduce new energy technologies, such as solar energy, geothermal energy, biomass energy, etc., to promote more sustainable urban heating facilities.

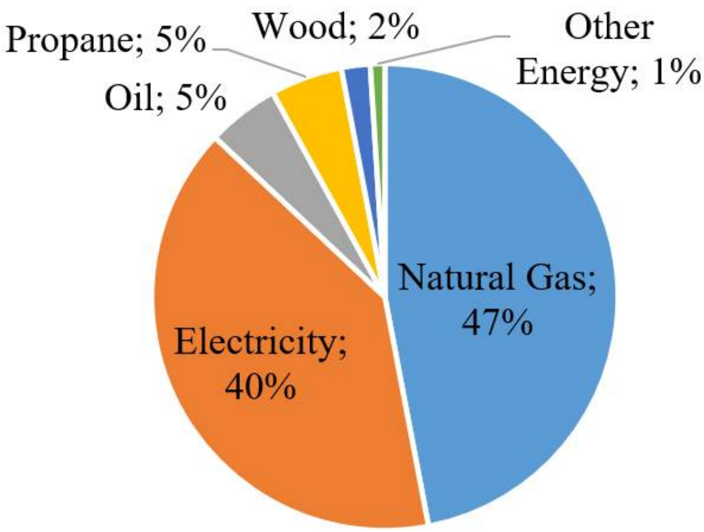

Fig. 1.3 – Winter heating fuel consumption in the United States

In addition, Ukrainian cities are also investing in the development of infrastructure to improve the quality of heating and enhance its reliability, while reducing energy consumption. In general, the development of centralized heating technology in Ukrainian cities is in a good trend. Now it has begun to introduce new energy technologies and invest in the development of infrastructure to gradually promote the transformation of the energy structure. Future development will also move in a more sustainable direction to provide reliable heating services for local people.

Germany's heating technology is relatively advanced. In 1972, it began to study heat metering technology and heat meter detection technology, and established inter-city heating systems. Heat metering has entered a mature period of private participation in services. Nordic countries started heating early, with large investments, excellent equipment, mature technology, and perfect control methods. The heating system operates stably and has good results.

Denmark is a country with scarce natural resources. In addition to oil and natural gas, there are few other minerals, and since the 1990s, there have been climate problems. Therefore, in order to reduce dependence on fossil fuels, improve energy utilization, and reduce emissions of CO_2 and other pollutants, regional energy systems have great potential. The Danish government is also vigorously supporting the development of regional central heating systems and vigorously developing renewable energy [11,12]. At present, nearly 50% of Denmark's heating needs are provided by regional heating systems [13]. According to the Danish Statistics Bureau, regional central heating accounts for 53.2% of Denmark's total heating; centralized heating accounts for 36.58%. Most of the heat energy is provided by thermal power plants, forming a situation where cogeneration is dominant and wind energy, bioenergy, tidal energy, solar energy, a small amount of fossil fuels and other energy sources are combined and renewable. Denmark is one of the earliest countries in the world to develop renewable energy and has achieved the most significant results. The integration of renewable energy in regional heating systems is the most important goal that still needs to be achieved.

Development status of Asian countries. The construction of urban centralized heating in China started relatively late, in the 1950s. However, with the rapid growth of the national economy and the improvement of its comprehensive strength, the centralized heating industry in China's cities has developed rapidly. In 2010, 315 cities in China had built centralized heating facilities, the cumulative area of newly built energy-saving buildings in China reached 4.86 billion square meters, the cumulative area of heat metering installation reached 360 million square meters, and the area of centralized heating in Chinese cities reached 9.251 billion square meters in 2020. At present, China's centralized heating has been gradually promoted from large cities to some small and medium-sized cities, and has gradually formed a situation in which cogeneration is the main heat source and other heat sources are supplemented. In order to make the development of centralized heating receive policy support, China has successively issued "Several Opinions on the Development of Cogeneration", "Guiding Opinions on the Pilot Work of Urban Heating System Reform" and "Opinions on Further Promoting the Reform of Urban Heating System", etc., which have created favorable conditions for the rapid development of urban centralized heating. According to statistics, by the end of 2023, the area of centralized heating in Chinese cities will be 10.603 billion square meters, more than double that of 2014. According to forecasts, with the continuous improvement of residents' living conditions and the continuous enhancement of energy-saving and environmental protection awareness, the area of centralized heating in Chinese cities will be further expanded.

In recent years, China's centralized heating has developed rapidly, with a great increase in both heating capacity and the scale of the heat network, and the popularity and application areas of centralized heating are becoming more and more extensive. However, behind the rapid development of centralized heating, there are also some problems. The most prominent problem is that the energy consumption for heating remains high. The energy consumption of China's heating system is 2 to 4 times that of the same latitude in Europe. There are three main reasons: First, the insulation of the enclosure structure is poor; second, the operation efficiency of the heating system is not high, the transmission energy consumption is high, and the heat user adjustment method is not good, resulting in the simultaneous existence of overheating and underheating problems, and a lot of heat waste; third, the heat source efficiency is generally low, the heat source heating capacity does not match the heat user demand, the operation and scheduling need to be improved, and the heating planning and decision-making lack theoretical guidance and support. Another issue that cannot be ignored is the increasingly serious environmental pollution caused by centralized heating. China's centralized heating sources are mostly coal-fired thermal power plants and regional coal-fired boiler rooms, and the various pollutant emissions caused by coal burning account for a high proportion of total emissions, as shown in Figure 1.4.

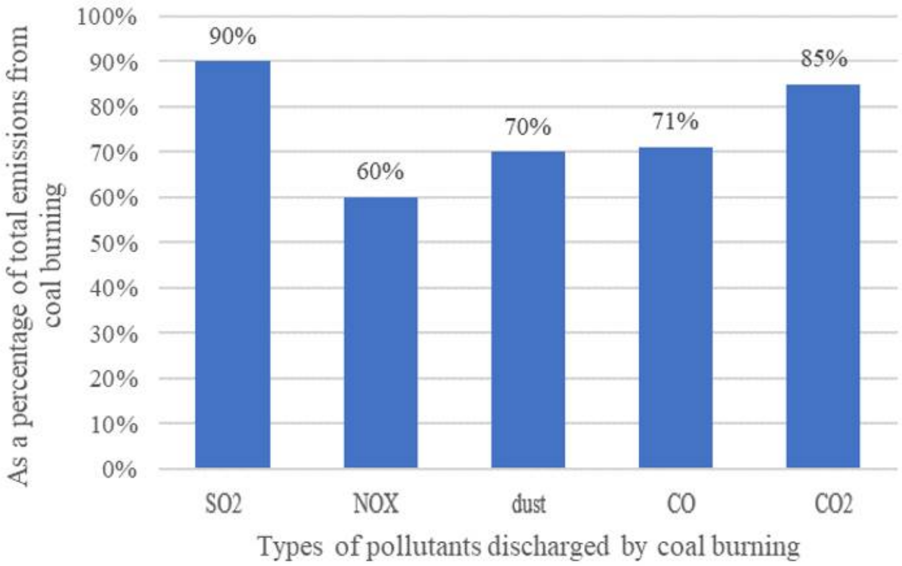

Fig. 1.4 – Major pollutants from coal combustion and their shares in China's total emissions

Pollutant monitoring data also show that a large amount of coal burning in the heating period poses a great threat to the urban ecological environment. Not only is the content of SO_2, NO_x and Total Suspended Particle (TSP) in the atmosphere significantly related to a large amount of seasonal coal burning, but also the health status of urban residents is affected by this. Heavily polluted cities have seen an increase in the prevalence and mortality of respiratory diseases. According to the monitoring data of environmental monitoring station in Urumqi, Xinjiang, China, the concentration of SO_2 in the atmosphere in the city's heating period once reached 15 times of that in non-heating period, and the concentration of NO_X was nearly 2 times of that in non-heating period. In addition, the greenhouse gas CO_2 has become the focus of the world. At present, China's annual CO_2 emissions exceed 6 billion tons, surpassing the United States. As can be seen from Figure 1.2, CO_2 emissions from coal burning account for about 85% of the total emissions. Therefore, how to reduce CO_2 emissions from heating system has become one of the keys to successfully achieve greenhouse gas emission reduction in China.

China began to develop central heating with power plants as the heat source roughly in the mid-1990s. At present, the main heating methods are cogeneration of heat and power, hot water regional boilers, supplemented by ground source heat pump, water source heat pump, air source heat pump and other new energy sources. With the national emphasis on environmental protection, urban central heating has become the mainstream. However, the operation management and control technology of the heating system is not mature, and the automation level is still relatively low. From the whole point of view, the intelligent heating can not keep up with the development of the scale of heating, which affects the play of the advantages of central heating.

The heating system is huge, and the intermediate heat exchange stations are scattered and numerous. It is difficult to achieve pipe network balance solely depending on human adjustment. Meanwhile, due to the complex system, pipe network aging causes frequent accidents [17]. Between the stations, between the buildings are easy to appear near the hot far cold phenomenon, so there is a "competition for food", especially the long haul pipeline, in the middle of a level or two relay pumping station, supply and demand do not match, the operation condition is not ideal, in order to ensure that the end of the heat, will increase the temperature or increase the flow at the cost of greater energy waste. This requires real-time dynamic data and improves the monitoring ability of the central control room [18]. With the development of heat network monitoring system, heat supply management has risen from manual meter reading, station management and passive maintenance to station room automatic monitoring and unattended, and the rudiment of intelligent heat supply pipe network has initially taken shape.

With the development of technological progress, heating technology is also constantly being updated. Many heating companies have tried to increase the heating temperature and the amount of circulating water to ensure heating for users and solve the problems of uneven heating and cooling and hydraulic imbalance. In terms of adjustment methods, they have also replaced simple quantity adjustment or quality adjustment with quality-quantity adjustment. For long-distance pipelines, more complex ring pipelines are used to supplement branch pipelines, and dual or multiple heat sources are even used to improve heating reliability [19]. This makes the heating system more complicated. Simply relying on human adjustment can no longer meet the heating needs. Heating companies use computer technology in heat source production and heat network distribution to achieve remote monitoring, which is the initial stage of management informationization and intelligent construction.

At present, China's heating industry has its own industry standards. Most newly built heating stations are equipped with advanced digital instruments, sensors and control devices, which basically realize the automatic control of a single heat exchange station and remote data monitoring of multiple stations. Some cities even have unmanned heat exchange stations. The dynamic data collected by the large-scale modern instruments in the heating system during the heating season are uploaded to the monitoring center of the heating enterprise through the network. The operation and management personnel can understand the operation status of the system at any time on the computer screen and set control targets for the equipment in the station according to the daily dispatch instructions. At the same time, the heat exchange station automatic control system can adjust and optimize the operation according to the changes in outdoor weather temperature without human intervention, saving a lot of manpower and financial resources for the enterprise. However, there is no unified standard for intelligent heating network, and various enterprises are still in the exploratory stage. Although some heat exchange stations are equipped with control devices, due to the lack of unified standards, the design level of the control system varies greatly. Most of them lack linkage with the monitoring center and can only upload data, but cannot achieve remote control, which cannot be considered as true automatic control [20].

Many heating companies have also begun to try to use geographic information systems, but their application has only remained at the primary stage of using massive amounts of data to generate simple data curves and data reports. Operation and management personnel still mostly use traditional manual control methods to issue dispatch instructions, but do not play the role of massive data in operation and dispatch, resulting in a waste of information resources. With the advancement of modern communication technology and control technology, the application of Internet of Things technology, and the development of cloud computing and big data technology, China has also begun to pay attention to the intelligent construction of heating systems. Some heating companies have begun to implement the development and construction of intelligent heating systems.

There is still a lack of unified understanding of smart heating in China, and technical research has just started [21]. With the increasing awareness of energy conservation and environmental protection in recent years and the development of communication technology, we should learn from and draw on the achievements of real-time monitoring, design and construction, equipment quality, and technical content of advanced centralized heating countries abroad to explore the construction of smart heating networks suitable for China.

Japan mainly develops district heating [22,23], which is relatively small in scale. The largest heating area is 3.386 million m^2, located in the northeastern region of Japan. The heat sources for heating are mainly natural gas, electricity, oil, coal gas and biomass energy. Japan pays great attention to the utilization of industrial waste heat, waste incineration heat, domestic sewage waste heat, air energy and other energy [24], reducing or even eliminating coal-fired heating. According to statistics, Japan has stopped using coal as a heat source for heating since 2009.

Based on climatic conditions, South Korea implements heating throughout the country, but the heating time is slightly different between the north and the south. The heating period in the south is from November to March of the following year, and the heating period in the north is from early November to mid-April of the following year. South Korea is a country with relatively scarce energy. In order to reduce energy consumption and greenhouse gas emissions, South Korea has actively developed centralized heating. The energy for heating is mainly natural gas and various oil products, and coal is basically not used [25]. Different residential buildings in South Korea have different heating methods. Korean residential buildings include high-rise residential buildings, collective residential buildings and individual residential buildings. Since Koreans have a "sitting and lying" lifestyle, residential buildings basically use floor heating, that is, floor heating. Individual heating is to set up a small heating boiler on the user side, which has good controllability. In South Korea, the heat source for individual heating comes from natural gas and kerosene. In addition, South Korea is developing regional heating using waste energy as fuel. It is estimated that 8% of the heating demand in South Korea is provided by waste energy, which helps South Korea gradually get rid of its dependence on fossil fuels [26]. South Korea generally uses regional boiler rooms and cogeneration as heat sources to heat buildings in the region.

Problems with central heating. With the continuous development of the economy of various countries, the acceleration of urbanization, and the improvement of people's living standards, urban heating has developed rapidly, especially the demand for urban centralized heating has gradually increased. With the acceleration of urbanization and the gradual deepening of people's understanding of resources and environmental protection, as a form of heating strongly supported by countries around the world at this stage, the scope and scale of urban cogeneration centralized heating has continued to expand, and its development prospects are broad. However, compared with developed countries in heating, China's cogeneration centralized heating still has many problems, such as complex heating network problems, the failure of thermal power stations to play their due role, and the low comprehensive utilization efficiency of centralized heating energy [27]. Therefore, under the premise of sufficient analysis and research, how to take practical measures to improve the centralized heating rate and reduce resource waste and environmental pollution is of great theoretical and practical significance to the sustainable development of urban centralized heating in China.

(1) Inadequate overall planning. The overall planning and design level are not enough, so energy saving cannot be implemented. The current design standards for indoor heating do not systematically stipulate the specific technical requirements of heating equipment, and do not reflect the actual level of current energy saving technology. At the same time, in the process of centralized heating for heat users, the design and planning departments still use the old design concepts to this day, which makes it impossible to implement energy saving, resulting in natural deficiencies [28].

At present, with the continuous improvement of people's living standards, the requirements for the comfort of living environment are also getting higher and higher. Take China as an example. In the past, many urban buildings south of the Yellow River did not adopt heating measures, but in the new era, more and more cities provide centralized heating for urban buildings. In particular, in recent years, cities south of the Yangtze River have begun to provide centralized heating in winter. Whether it is old city renovation or new city construction, many cities lack overall planning in the process of going from no heating to heating, resulting in a situation with many small boilers, many chimneys, and a small heating range.

(2) There are many problems in the design of heating network. In the process of urban reconstruction and construction, the continuous popularization of centralized heating has made the coverage of urban heating pipe networks increasingly larger. However, due to unscientific problems in the design of heating networks, the phenomenon of poor heating effects in major cities often occurs. Most of them are unscientific and closely related. The most common phenomenon is that the heating of nearby users is overheated, while the heating of distant users is not hot. The management layout of the pipe network is of great significance to the efficiency of centralized heating [29,30]. Only scientific and reasonable design can ensure high-quality heating, reduce energy consumption, save construction costs, and meet user needs. At present, many details are not considered carefully when designing the heating network. For example, the problem of condensate recovery will lead to water shortage due to heating temperature, material selection, construction technology and quality. If it is taken into consideration during the design, it will reduce heating consumption, improve heating quality, and enhance the service life of the pipeline. Another example is the insulation problem of heating pipelines. Strengthening the insulation design of heating pipelines can reduce the heat of heating network pipelines and reduce energy consumption.

(3) Unscientific heat billing. Lack of rational calculation of heat makes charging difficult. At present, the charging method for centralized heating in Chinese cities is still concentrated on the model of charging according to the heating area, which will lead to some problems, such as the inability to accurately measure the heat consumption of heat users. Since the heat energy consumed by heat users cannot be accurately calculated like water, electricity and gas, the collection of heat fees consumed by users cannot be carried out according to the actual situation, which limits the enthusiasm of heat users for energy saving and timely payment, making it difficult for various heating units to operate sustainably. For users with higher heating temperatures, there is no awareness of energy saving; for users with lower heating temperatures, there are losses and customers have greater complaints. At present, the country advocates centralized heating in cities, and also emphasizes the importance of energy conservation and emission reduction. Therefore, if a scientific heat charging method can be adopted, more users can choose heat energy consumption according to their needs, thereby achieving the goal of energy conservation and emission reduction. This billing method can also reflect the actual electricity consumption of users.

Heating production is a large workload, with heavy tasks and complex contents, often involving many units and users. Therefore, how to effectively manage the heating system, project process, cost control and enterprise resources requires strengthening environmental protection and energy-saving technology reforms, and requires a powerful intelligent information management platform to provide support. This paper explores the advanced management ideas represented by the application of informatization to promote the establishment of a new management system, make full use of information technology to improve the technical level and management level of enterprises, improve the quality of heating, provide sincere services, achieve environmental protection, energy saving and harmonious heating, and promote the transformation of traditional industries from extensive to intensive.

Necessity of intelligent heating network.

(1) Necessity of overall energy control. China is a major coal energy consumer, with prominent contradiction between energy supply and demand, prominent energy security problems, low energy utilization efficiency and serious environmental pollution. Therefore, with the increasing requirements for urban air environment protection and the adjustment of urban energy structure, sustainable development faces great pressure. It also puts forward the strategy of sustainable energy development, which is "energy saving priority, security of supply, optimization of structure and environmental friendliness".

Since the buildings were all non-energy-saving buildings before 2007, the users could not use heat independently, and the heating facilities are aging, resulting in the overall efficiency of the heating system is not high; The operation efficiency of small cogeneration boilers is low, and the development of heating is too fast, so that the pipe diameter is getting bigger and bigger, the pipeline is getting longer and longer, and the heating system is getting more and more complex, forming the operation mode of "large flow and small temperature difference", which affects the energy saving level of the system. According to statistical calculation, the average coal consumption of urban central heating in each heating season is about 25-35 kg/m^2. If 50% and 65% energy saving is achieved, the coal consumption of heating can be reduced to 15-18 kg/m^2, that is, 10-17 kg/m^2 can be saved. The national heating area reaches 10 billion square meters [31,32]. It can be seen that the amount of energy saving reaches 1.0-1.7 million tons of standard coal. Urban heat supply has become an important part of energy conservation and emission reduction.

(2) Necessity of overall control of centralized heating system. As the scale of heating continues to increase, urban heating will inevitably face the following five challenges:

First, in order to protect the atmospheric environment, due to the shortage of coal resources, clean energy is a challenge to coal-fired cogeneration and regional boiler rooms. Heating companies are faced with a series of problems: reducing initial investment, improving the heating system, reducing heating costs, and creating the greatest benefits for users.

Second, due to the lack of a complete long-term heating plan, the plan often lags behind the goals of urban economic development, resulting in the construction of heating sources lagging behind the development of heating demand. In the future, there will inevitably be serious heating shortages. Or heating projects are mostly short-term behaviors, blindly expanding construction projects, and the heat load cannot keep up after the heat source is built, resulting in the idle heat source.

Third, due to the expansion of heating area and the increase of heating facilities, heating companies will inevitably face great pressure on the operation and management of the heating network; at the same time, due to the huge investment in the construction of heat sources, heating companies will also face huge financial pressure.

Fourth, the current level of automation and operation management of centralized heating needs to be improved. Many heating companies use many seasonal workers due to the seasonality of heating. The instability of seasonal workers and their lack of knowledge and experience pose hidden dangers to the safety and stability of the heating network.

Fifth, with the increase in the life of pipelines, the heating network will inevitably face more safety challenges such as leakage and pipe burst.

Therefore, based on timely meeting the heating needs of future users, improving the operation management level of the heating network, reducing the investment and construction costs of heating facilities, and improving the operation safety of the heating system, the best way is to improve the automation control level of the heat exchange station, upgrade and improve the construction of the upper monitoring center, build a heating network operation and dispatching management system, and build an energy consumption management platform based on the heating network operation and dispatching management system. In this way, the operation management level of the heating network can be improved, the heating potential can be tapped, the operating energy consumption of the existing system can be reduced, the saved heat can be used for the access of new users, and the operating status of each node of the heating network can be monitored in real time to discover the potential safety hazards of the heating network in advance or to discover, respond and deal with them quickly when an accident occurs.

(3) Necessity of energy conservation and consumption reduction. For heating companies, the basis of energy conservation is to clearly understand the energy consumption of heat sources, stations, and users at all levels, and to check whether the operating parameters in the station match the outdoor temperature and whether the indoor temperature of the user meets the standard. In other words, effective energy consumption analysis can provide a reliable basis for the company's efficient and

energy-saving operation, thereby saving the company's operating costs and improving economic benefits. The establishment of a production scheduling system can comprehensively and systematically analyze and calculate the production and operation costs of the heating season. Through analysis and calculation, the heating cost can be effectively controlled, achieving the purpose of reasonable allocation of resources, balanced heating, energy conservation and consumption reduction, and expansion of development.

Development trend of urban centralized heating.

(1) Larger and larger scale. In the future, as people's quality of life gradually improves, the demand for winter heating will become more and more widespread. There will be more and more cities with heating, and the scale of urban centralized heating will become larger and larger.

(2) Enhanced overall planning. As the country gradually strengthens the planning of urban construction, the heating planning model that was designed only when needed will be improved. The heating planning model that focuses on the overall planning and development of the city will gradually emerge and help the development of the city.

(3) Gradually optimized heating network design. The design of the heating network is of great significance to the heating effect and energy conservation. More and more design units have accumulated more experience in heating network design in practice. In the new urban planning, the following four more scientific heating network design schemes are provided. At the same time, the existing heating network is gradually optimized to improve its heating efficiency.

Scheme 1: Reasonable design of pipeline layout and pipeline direction. Pipeline and pipeline setting is the core content of the entire pipeline system. Whether the pipeline layout and pipeline direction are reasonable directly affects the heating effect. When designing the pipe network system, it is necessary to carefully examine and scientifically design, do a good job of drawing analysis, fully understand the design intent, reasonably lay out the pipe direction, and consider reasonable optimization and arrangement from the perspective of the entire heating system to ensure the rationality of the entire centralized heating pipe network so that users at both ends can enjoy standard heating services [33].

Scheme 2: Strengthen the solution to the condensation problem. Condensation is a prominent problem in the centralized heating pipe network system. In order to effectively prevent condensation from affecting the centralized heating pipe network. The selection and inspection of insulation materials should be strengthened, new pipes should be used to avoid condensation, and experiments and tests should be conducted on the pipes and insulation materials used. Secondly, during the construction process, pipes that penetrate the wall should be equipped with insulation protection sleeves to ensure the continuity and tightness of the pipes.

Scheme 3: Use polyurethane as insulation material. Polyurethane is more suitable as insulation material than rock wool. Polyurethane not only makes up for the shortcomings of rock wool, but also has better insulation performance than rock wool.

Scheme 4: Ensure the smooth flow of pipes. If there are foreign objects in the central heating network, it will affect the water circulation system of the heating network and seriously affect the heating quality. Therefore, when designing the pipeline installation, you must carefully check to ensure that there are no foreign objects in the pipeline, remove scale and rust from the pipe wall, and ensure that the inner wall of the pipeline is clean before sealing it for installation. This must be taken into consideration when optimizing the design of the central heating network.

(4) Green energy-saving concepts will be widely used. At present, the whole world attaches great importance to the concept of green energy-saving. Urban centralized heating is a centralized energy consumption in a specific season. If the concept of green energy-saving can be integrated into it, it can save resources and promote environmental protection. For example, in the selection of heating energy, coal combustion is currently the main heating energy. In the future, human resources will be seriously scarce, and using nuclear power as the main energy source for heating may become a new trend [34].

(5) Reliability is gradually improving. In urban centralized heating, heating outages are the main problem of user complaints. In the future, the reliability of heating can be improved by designing a multi-heat source network heating method. That is, more than one heat source is connected at the same time, and when the main heat source fails, other heat sources can immediately supplement the heat. This avoids the reduction of user experience due to human failure or the occurrence of major accidents, and maximizes the reliability of heating.

(6) The concept of intelligence is gradually advancing. The future is an era of intelligence, and all walks of life will be permeated with the concept of intelligence. In urban heating, intelligent means such as intelligent temperature control and intelligent billing will gradually advance. By installing intelligent control equipment at the user

end, customers can choose to control the indoor temperature by themselves, that is, they can adjust the indoor temperature on demand through remote control. And they can make more scientific and reasonable intelligent billing according to the customer's heat usage and usage period [35]. For example, when the user is not at home during the day, a lower temperature can be set. The indoor temperature can be automatically adjusted half an hour before the user returns home, so that the user has a suitable temperature when he returns home. This can greatly reduce the consumption of heat sources and comply with the national energy conservation and emission reduction strategy. For heating companies, using big data technology for data mining and applying intelligent decision support systems will also become a major trend in the future. When designing, new technologies and new products should be fully considered, so that the management and control of heating companies tend to be intelligent. In this way, the heating system can meet the needs of energy conservation and emission reduction while operating in the best state. In short, from the perspective of energy conservation, urban central heating will surely develop on a large scale. In the future, as the level of informatization gradually advances, designers of urban heating systems must actively explore and actively accept new things, new methods, new equipment, and new software, and quickly apply them to the design of urban central heating systems [36].

1.3 Harmful emissions of central heating boilers, the causes of their formation, impact on the environment and humans

Boiler in the process of operation will inevitably discharge air pollutants, directly affect the quality of air environment. It is very important to strengthen environmental control of boiler air pollutants and reduce emissions. Boiler is a facility that converts chemical energy of fuel (solid, liquid and gas fuel) into heat energy by combustion, which is widely used in power, petroleum, metallurgy, chemical industry, heating and other production and life fields [37]. In the process of boiler operation, fuel combustion generates a lot of combustion heat, but also produces a variety of combustion products, mainly including carbon dioxide, sulfur dioxide, nitrogen oxide and particulate matter. Among them, carbon dioxide is a greenhouse gas, sulfur dioxide and nitrogen oxide can form acid rain under certain conditions, and particulate matter can form dust in the atmosphere or be inhaled into human lungs and cause disease. Large capacity boilers generally process the combustion products through the dust removal, desulfurization and denitrification device after the tail heating surface, and then discharge them into the atmosphere, becoming atmospheric pollutants. And many small capacity boilers will all combustion products directly discharged into the atmosphere, to the quality of the atmosphere and people's living environment quality caused serious damage.

The operation mode of the heating boiler is to use the heat energy generated by the combustion of materials to supply the normal operation of the boiler. Usually, the main raw material used is coal, but there will be excessive consumption and emissions during the combustion of coal, and a series of chemical reactions will also occur. For example, incomplete combustion, excessive combustion and other phenomena will not only cause serious pollution to the environment, but also reduce the normal service life of the boiler to a certain extent. During the operation of the boiler, it is inevitable to emit air pollutants, which directly affects the quality of the atmospheric environment. Strengthening the environmental governance of boiler air pollutants and reducing emissions, the monitoring of boiler air pollutants is crucial.

Pollutants contained in boiler flue gas pollution. Nowadays, the problem of air pollution has become a pressing issue for people. We should effectively control the sources of pollutant emissions to protect the ecological environment. During the operation of heating boilers, coal is burned, which often produces a large amount of pollutants. Effective control measures should be taken for heating boilers. The generation of smoke from heating boilers is mainly due to the incomplete combustion of some chemical substances, which produces a large amount of black tiny particles. As these substances continue to increase and condense, and float in the air, they cause serious damage to the environment. If these smoke substances enter the human body, there is a high risk of infection and poisoning. This is mainly because some metal elements are likely to be combined with smoke. Secondly, sulfur dioxide pollution is a serious gaseous pollutant and is also an important gaseous pollutant that China is currently controlling. There are often many sulfur-containing components in raw materials such as coal. If sulfur dioxide is not burned fully, it may also produce sulfur dioxide, which is likely to form acid rain in the atmosphere, causing serious damage to our ecological environment [38]. In addition, nitrogen oxide pollution, if this pollutant enters the human body, it is very likely to cause the disease problem of methemoglobinemia. If it is combined with other pollutants under certain conditions, it may even cause photochemical smog pollution. Finally, carbon dioxide pollution. Global warming today is mainly caused by the increase in carbon dioxide levels.

(1) Smoke and dust. Smoke and dust are extremely fine black particles, mostly produced by incomplete combustion of fuel, and boiler flue gas is one of the important sources of air smoke and dust. Generally, the main components of smoke and dust are

silicon dioxide, aluminum oxide, iron oxide, calcium oxide and unburned carbon particles. In environmental pollution, due to the wide variety of atmospheric pollutants, common smoke and dust include black smoke, red smoke, yellow smoke and gray smoke, and the composition and source of smoke of different colors are also different. According to the form, they can be divided into two categories, namely particulate pollutants and harmful gases. Therefore, smoke and dust will contain a large number of unburned fine particles. These particles are transmitted to the atmosphere by hot air, will float in the air for a long time and gradually accumulate, which not only hinders the normal development of society, but also forms an air pollution situation that is difficult to improve. Moreover, it is very easy to absorb metal elements. When inhaled by the human body, it will combine with the blood and organs inside the human body, causing human poisoning.

(2) Sulfur dioxide – SO_2. As a common gaseous substance, SO_2 is not only highly irritating to the human respiratory tract, but also has negative effects on plants, such as bleaching spots, growth inhibition, leaf damage and reduced yield. The scope of its influence is large, the depth of the harm is inestimable. Under normal circumstances, SO_2 colorless, but has a strong irritation, will seriously harm human health, can make the human body produce a series of respiratory diseases, at the same time, but also can fuse with the blood, causing human body poisoning. For example, coal and other related fuels contain higher sulfur element, and in the actual combustion process, a higher concentration of SO_2 will be produced. However, when the concentration of SO_2 is too high, it will combine with water to form acid rain, which will cause damage to surface materials, endanger human life and health in serious cases, and also cause irreversible damage to ecological environment [39].

(3) Nitrogen oxides – NO_X. Nitrogen oxides is the general term for nitrogen and oxygen compounds, mainly including NO and NO_X, among which, NO_X in the atmosphere mainly comes from natural and man-made emissions. Under high temperature combustion conditions, nitrogen oxides exist mainly in the form of NO, and the initial emission of nitrogen oxides is about 95%. In daily life, NO_X is one of the most common atmospheric pollutants, mainly including factory emissions of gas, nitrogen fertilizer plant, organic intermediate plant, nonferrous and ferrous metal smelter some production process, according to statistics, annual emissions of NO_X to the atmosphere can reach tens of millions of tons. NO usually irritates people's respiratory system and can be toxic by combining with heme to form nitroso-heme. Similarly, NO_X can also seriously stimulate people's respiratory system, and make heme nitrification, the harm is greater than NO, if the human body inhalation too much, the substance will lead to irreversible damage of hemoglobin and lung tissue, and even lead to the human capillary alveolar wall permeability is too strong, resulting in edema.

(4) Carbon dioxide – CO_2. Carbon dioxide is a colorless, tasteless and odorless gas at room temperature. In the process of boiler fuel combustion, the incomplete combustion of fuel will produce CO_2 which is harmful to the environment. In addition, excessive CO_2 will directly affect the atmosphere, so that the sun's radiation does not have a barrier and absorbers, but directly radiates to the earth surface, forming diffusion, resulting in rising earth temperature and greenhouse effect. According to the prediction of relevant experts, if the emission of CO_2 continues to rise, the earth's surface temperature will rise by about 30°C in about 30 years, and the temperature at the poles will rise by 1°C. In this way, glaciers will melt, sea level will rise, and some low islands and coastal cities will be swallowed by sea water, thus causing incalculable losses [40].

(5) Distribution of typical pollutants in coal-fired boilers. The proportion of pollutants in boiler flue gas varies depending on the fuel type, combustion technology and operating conditions. Taking coal-fired boilers as an example, Figure 1.5 shows the distribution of the above four major coal-fired boiler pollutants and other pollutants (carbon monoxide, volatile organic compounds, heavy metals).

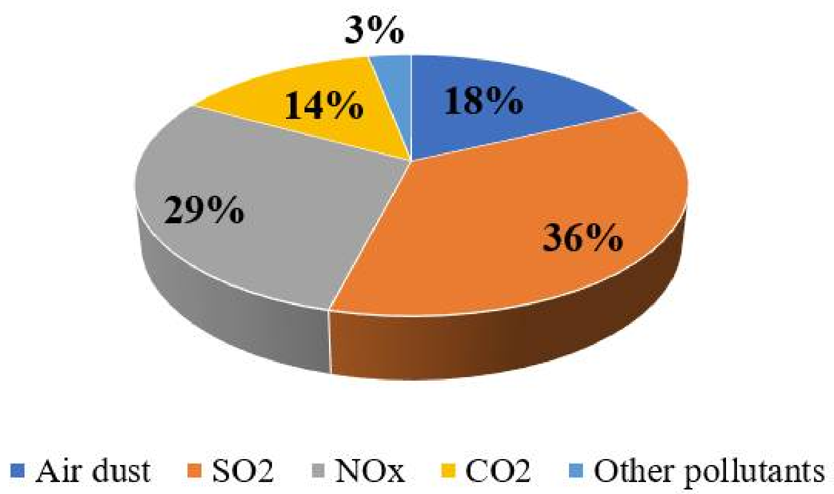

Fig. 1.5 – Distribution of typical pollutants in coal-fired boilers

Boiler flue gas pollutants are of various types and their distribution is affected by combustion conditions and fuel type. Controlling these pollutants is critical to environmental protection and human health.

Causes of boiler flue gas pollution.

(1) Unreasonable control of secondary wind pressure. In the process of boiler operation, if we want to further improve the economic value and use efficiency of boiler fuel, we must make reasonable adjustment and improvement according to the actual situation. Therefore, secondary air pressure can be controlled to ensure the combustion in

the furnace, so as to effectively avoid fuel waste and serious pollution [39]. In the actual use process, the vast majority of boilers will produce different degrees of pollution and other problems, which is mainly because the control of secondary air pressure is unreasonable and unscientific, and the pollution inside the furnace is mostly caused by the air coefficient, as well as a series of problems caused by the rise of smoke exhaust temperature.

(2) Coal material moisture is too high. In the actual operation of the boiler, if the water content of the fuel is too high, it will lead to insufficient fuel combustion. Especially, when the water content of one part of the boiler is too high, high temperature steam will be generated, and then the water vapor and flue gas will mix and react, resulting in the occurrence of smoke exhaust pollution inside the furnace [41]. At the same time, fuel moisture will also have a direct impact on the internal exhaust temperature, and even form acidic substances, which has fatal damage and corrosion to the boiler itself, and will directly affect the normal service life of the boiler.

(3) Coal quality issues. The boiler should be inspected in the process of use, but also the quality of the coal itself should be regularly controlled and spot checked to ensure that the fuel used in the boiler is of high quality.

Energy saving and environmental protection measures for boiler flue gas pollution.

(1) Adjusting the secondary air pressure. During the actual operation of the boiler, the overall operating efficiency of the boiler can be effectively improved by properly adjusting the secondary air pressure. If the secondary air pressure is in an unreasonable and unscientific state, it will reduce the combustion efficiency of the fuel, which will cause the exhaust gas temperature to rise. In the long run, it will greatly damage the boiler and shorten the normal service life of the boiler. Therefore, during

the actual operation, the air pressure must be strictly controlled. Through scientific research and analysis, the core reason for the failure of the secondary air pressure to meet the standard lies in the fan itself. Therefore, if you want to truly adjust the air pressure change, you must start with the induced draft fan. You can increase the air pressure by replacing the induced draft fan, so that the oxygen content in the furnace will increase rapidly, and the secondary air pressure will be increased from the previous 5 kPa to 9 kPa, thereby effectively improving the penetration of the secondary air pressure, improving the combustion efficiency, reducing the combustion center temperature in the boiler, and effectively ensuring the combustion time inside the furnace. At the same time, it also reduces the exhaust gas temperature, improves the operating efficiency, and extends the normal service life of the boiler..

(2) Blending fuel. In the actual production and use process, before the fuel is sent into the boiler, other auxiliary fuels can be added to ensure the normal combustion of fuel, mainly in order to prevent insufficient combustion and combustion efficiency caused by too high water molecules. During the actual production, the average calorific value should be above 2 000 kcal to ensure the stability of the fuel and the bed temperature is always constant. At the same time, the smoke exhaust temperature should also be ensured within the control range. But when it comes to the right mix of fuels, make sure you have the right mix of ingredients. For example, high calorific value and low calorific value fuels can be matched; The mixture of high moisture fuel and low moisture fuel can better improve the efficiency of fuel combustion in the furnace, so as to effectively improve the pollution problem of boiler smoke, reduce the smoke carried in the exhaust smoke, and ensure the normal operation of the boiler. In addition, during the fuel input period, it can

also reduce the mud content of the fuel and make appropriate allocation according to the relevant proportion to improve the heating area and conduction efficiency.

(3) Control the quality of coal. The combustion quality of the boiler is unreasonable and unscientific, which is the core reason of the high exhaust temperature. Therefore, during the improvement of the boiler, we should pay attention to the change of smoke exhaust temperature, at the same time, we should pay more attention to the control of fuel quality and other related issues. First of all, the water content of coal should be strictly controlled. If the water content of the fuel itself exceeds 35%, the boiler will be affected by water molecules in the combustion process, thus reducing the combustion performance of the fuel and directly affecting the combustion temperature of the flame. There will even be insufficient combustion phenomenon, resulting in debris dust mixed into the smoke, so that the smoke furnace smoke temperature inside the boiler, which not only causes air pollution and secondary combustion, but also affects the normal use of the boiler efficiency. Therefore, in general, to strictly control the water content of fuel, appropriate measures and treatment can be taken to effectively reduce the smoke temperature of smoke furnace [42].

(4) Improve boiler design quality. To truly improve the pollution problem of boiler flue gas, it is necessary to make improvements based on actual conditions, especially the reasonable design of the boiler's heating surface. During the design period, it is necessary to continuously calculate the actual efficiency of its combustion, clarify the internal structure and related dimensions of the furnace, achieve the optimal capacity and the optimal load of the heating surface, and then conduct a comprehensive analysis based on relevant data such as the internal volume heat load of the furnace and

the outlet flue gas temperature to design the actual size of the boiler, but it must be selected strictly in accordance with relevant data. In this way, the soot blowing steam pressure can be increased to the greatest extent, which not only achieves the most ideal use effect, but also reduces the exhaust gas temperature to the greatest extent. It can be seen that by changing the soot blowing method, the normal operation efficiency of the boiler can be guaranteed to the greatest extent and its actual value can be fully utilized [42].

Taking the bag dust removal method as an example, bag dust removal is currently a more effective dust removal method. It is not limited by the operator's experience, can reduce the probability of the dust collector failing to start correctly due to instrument damage, can maximize the reduction of system failure rate, and improve the efficiency of the cleaning system. However, it is still necessary for relevant technical personnel to further conduct in-depth research and innovation on the scientific and technological aspects of bag dust removal through in-depth research on the particularity of soot-type environmental pollution, so as to make the technology more perfect and meet market conditions. At present, under the condition of normal operation of boiler equipment, the overall design technology level of bag dust removal technology, production technology of filter materials and other parts, and its economic tolerance have basically met the development needs of modern boiler equipment flue gas dust removal technology.

(5) Optimize the boiler blower and regulation system. In order to further improve the environmental protection of the boiler in the operation process, the focus should be on the scientific and reasonable use of the boiler blower and regulation system to improve the operation efficiency of the boiler. Generally, the boiler blower achieves low power loss through variable frequency technology speed regulation. The air

volume control is to adjust the air volume by the opening size of the windshield, but this method has not really played a role in saving electricity. Therefore, in recent years, with the advancement of science and technology and the increasing maturity of frequency regulation technology, relevant technicians have begun to use frequency converters to adjust the frequency of the power supply, thereby increasing the speed of the blower, and adjusting it at different times to achieve a reasonable air volume and achieve the purpose of energy saving. In addition, since the boiler has been in full load operation for a long time during the entire heating period, the use of variable frequency speed regulation can significantly reduce electricity. Therefore, it is necessary to attach great importance to the energy-saving methods of heating boilers, minimize the waste of fuel energy, and continuously improve the use efficiency of boilers to achieve sustainable development of the economic and social benefits of heating boiler operation.

(6) Innovative energy-saving and environmentally friendly technologies for heating boilers. In the actual operation of heating boilers, the combustion technology used is mainly to grind large pieces of coal, and then sprinkle the coal powder in the furnace with air to make it burn. Since the diameter of the powder particles is very small, they will burn quickly in a short time. Therefore, the use of this combustion technology can achieve a certain combustion effect, and the pollutants generated during combustion also meet the requirements of relevant policies and systems. With the advancement of science and technology, among the latest energy-saving combustion technologies developed in China, the effect of circulating fluidized bed technology is the most obvious. This method mainly grinds the lump coal into powder particles, and then converts the powder particles into powder when exhausting air, so that it can self-

ignite in the heating boiler; and a separator is set in the boiler to return the unburned particles mixed in the smoke to the furnace for a second combustion, so as to be reused repeatedly, thereby improving the combustion efficiency. After multiple cycles of combustion, the fuel can be burned in all directions inside the boiler, thereby effectively improving the use efficiency of the boiler and the combustion rate of the fuel.

In summary, during the actual operation of the heating boiler, there will be flue gas pollution and other phenomena. This problem will directly affect the normal use efficiency of the boiler and reduce the use value of the fuel. According to relevant studies, there are many reasons for boiler flue gas pollution, but it is mainly caused by insufficient flame combustion inside the furnace and scaling of the heating surface caused by excess air coefficient. Therefore, when reducing the temperature of the boiler, it is necessary to comprehensively consider various influencing factors, and also pay attention to related issues such as the overall design of the boiler and the quality of the fuel itself, so as to effectively improve the actual use efficiency and comprehensive economic value of the heating boiler [43].

1.4 Technologies for increasing the energy and environmental efficiency of municipal energy systems

Heating energy crisis. The most concerned and worrying issue in the world now is the energy problem, which will affect the development and survival of all of us. Both developed and developing countries attach great importance to their own energy reserves. With the rapid and sustainable economic development, low-carbon economy has gradually become the theme and focus of our lives. Problems in energy regulation are becoming more and more serious, especially in the heating industry. Insufficient resource supply has become an important constraint on economic and social development.

Since the oil crisis in the 1970s, many governments have begun to pay great attention to energy conservation and environmental protection. Before 1960, the main fuel for heating was coal, coke, wood and peat, and later it was changed to oil. Oil was on the verge of shortage. Denmark, as the first country to make an energy plan, focused on safe supply, energy conservation and finding alternatives to oil. Natural gas resources have become the best alternative to oil. In the 1990s, Denmark actively supported and signed the Kyoto Protocol. After more than 30 years of development, Denmark's national income has increased by 50%, but energy consumption has not increased, and the heating energy consumption per unit area has decreased by 50%, achieving efficient and diversified energy utilization. At the same time, the biggest benefit is that it has greatly reduced the environmental pollution caused by the burning of coal and oil. Copenhagen is the only capital in the world that has reduced its carbon dioxide emissions by 20% in ten years. In 30 years, the emissions of carbon dioxide, sulfur dioxide and nitrogen oxides have decreased by 50%, 35% and 80%-90% respectively, and remarkable achievements have been made in environmental protection.

The phenomenon of low energy utilization and large energy consumption caused by heating is still very common, which needs to be paid attention to. The low utilization rate and high consumption of heating energy are mainly caused by backward heating methods. There are several heating methods: centralized heating, coal-fired decentralized boiler heating and single heating. From the perspective of energy saving, environmental protection and economy, centralized heating is a more ideal heating method. However, the proportion of centralized urban heating is not large at present, and a large proportion of users use decentralized small boilers for heating. This backward heating method has caused huge waste in energy utilization. For this reason, this backward heating system must be reformed. Only by forming an energy-saving mechanism can it help improve the global environmental protection level and thermal energy utilization efficiency.

In terms of user heating, many cities also have serious energy waste in heating. From a technical perspective, poor insulation and airtightness of buildings will lead to large heat loss and low heat efficiency. From an institutional perspective, the heating billing method is charged according to the building area, rather than calculated and charged according to the actual heat consumption. This kind of buying and selling relationship in which the heating fee is disconnected from the heat consumption violates the objective law of the market economy. It cannot reflect the market basic principle of paying how much heat is used to users in terms of the amount of heat used, and denies the attribute of heat as a commodity, thus inhibiting heating energy conservation, making users lack the enthusiasm for energy conservation, and causing great waste of energy.

On the other hand, the energy reserves of any country are not optimistic. Even if they are very sufficient now, no one can guarantee that there will be no day of depletion in the future. For example, the coal resource reserves mainly used for urban heating in China are 90 billion tons, and the reserves are less than 100 years. In the past decade, the large-scale use of coal in China's steel industry and power industry has caused coal prices to continue to rise, exacerbating the shortage of thermal coal reserves, and making the thermal coal reserve rate in most cities below the warning line. Therefore, in the case of tight heating energy reserves and low utilization efficiency, it is urgent to solve the heating energy crisis. Strengthening government regulation of the heating industry and improving the regulatory system are the core of solving the energy problems in the heating industry. Only by standardizing the relevant systems can the loss and waste of resources be effectively reduced.

Environmental pollution caused by heating. Human survival and development are closely related to the natural environment. We are interdependent and interact with each other. It is our common wish to build a resource-saving society, protect the environment, achieve sustainable development [44], and ensure the sustained, rapid, coordinated and healthy development of the economy. Since the United Nations initiated the "First United Nations Conference on the Human Environment" in Stockholm, Sweden in June 1972, and put forward the famous "Declaration on the Human Environment", it was the beginning of the attention of governments around the world to the cause of environmental protection. In the past 50 years, various environmental problems have plagued us. The fertility of arable land has been decreasing. In Africa, Asia and Latin America, soil erosion is very serious due to the disappearance of forest vegetation, over-exploitation of arable land and overgrazing. The rising temperature and many densely populated areas will be flooded. The rising temperature has a serious impact on the ecosystem. Climate change and energy waste seriously threaten all mankind.

According to the research, the air pollution of many heated cities is more serious than that of unheated cities, especially the pollution of heating season is more serious than that of non-heating season. The total suspended particulate matter in the air during heating season is 70% higher than usual. The pollution caused by heating cannot be ignored. The pollution problem caused by heating mainly comes from the selection of heating heat source. Coal is a non-clean energy, which has a very strong negative effect on the atmospheric environment. The combustion of coal produces a large amount of carbon dioxide, sulfur dioxide and certain nitrogen oxides, so the combustion of heating source aggravates the environmental pollution. Moreover, the unsound heating method also aggravates the degree of pollution. Many scattered small coal-fired boilers not only consume a lot of energy, the dust removal efficiency is low, and the lack of effective environmental protection measures, causing serious environmental pollution.

Conclusions to the Chapter 1

1. A comprehensive analysis of environmental problems, environmental protection and energy-saving technologies in the field of heat supply was conducted, which made it possible to assess the current state and trends in the development of centralized heat supply in different countries of the world, to systematize technologies for increasing the energy and environmental efficiency of municipal energy systems, and to substantiate the feasibility of implementing the principle of rational implementation of energy-efficient measures and technologies.

2. The results show that energy-saving measures such as intelligent temperature control systems, double-layer facades, BIM technology, and the use of new energy have significant advantages in improving the energy efficiency of heating systems and reducing carbon emissions. Although these technologies have high investment costs in the initial implementation stage, in the long run, they can bring considerable economic and environmental benefits.

CHAPTER 2 THEORETICAL BASIS OF ENSURING SUSTAINABLE DEVELOPMENT OF URBAN HEATING SUPPLY

Urban heating has become a major pillar of security and an important part of citizens' lives and urban operations. However, the problems of traditional heating methods have attracted much attention, including energy structure problems, heating environment problems, equipment maintenance and upgrading problems, etc. [67]. The above problems show the huge challenges facing the sustainable development of urban heating. Therefore, studying the theoretical basis for the sustainable development of urban heating is of great significance to promoting the construction of an "energy-saving and low-carbon" urban heating system and ensuring the safety of urban heating development [68].

2.1 Basic provisions of the theory of sustainable development

The basic theory of sustainable development is an important concept, and its core is to achieve a balance between social and economic development and environmental protection. This theory is usually based on a sustainable development framework of input and results. Sustainable development is a complex concept, which includes systematic analysis, scientific evaluation and global thinking literacy related to sustainable development. Therefore, effective actions to promote the implementation of sustainable development must rely on systematic thinking and integrated development ideas from multiple disciplines and perspectives.

The concept of sustainable development. Since the concept of sustainable development was first proposed in 1980, scientists, sociologists, natural scientists, etc. have explained sustainable development from the perspective of their respective disciplines and given their own definitions.

(1) Sustainable development defined from the perspective of ecological environment and its protection. The concept of sustainability originates from ecology, namely "Ecological Sustainability". It mainly refers to the balance between natural resources and their development and utilization. In November 1991, the International Association for Ecology (IntEcol) and the International Union of Biological Sciences (IUBS) jointly held a special seminar on sustainable development. The results of the seminar developed and deepened the natural attributes of the concept of sustainable development, defining it as: "protecting and strengthening the production and renewal capacity of environmental systems". The sustainable development defined by American landscape ecologist R.T.T. Forman based on the concept of biosphere is another representative of sustainable development from the perspective of natural attributes, that is, sustainable development is "seeking an optimal spatial structure of ecosystems and land use to support ecological integrity and the realization of human desires, so that the human living environment can be sustained".

(2) Sustainable development defined from the perspective of social attributes. In 1991, the book "Caring for the Earth: A Strategy for Sustainable Living", jointly published by the World Conservation Union, the United Nations Environment Programme and the World Wildlife Fund, defined sustainable development as: "improving the quality of human life without exceeding the carrying capacity of the

ecosystem", and proposed nine principles for sustainable survival. Among these basic principles, it not only emphasizes that human production and lifestyle must be balanced with the carrying capacity of the earth and maintain the vitality and biodiversity of the earth, but also puts forward the values of human sustainable development and 130 action plans, emphasizing that the ultimate goal of sustainable development is human society, that is, improving the quality of human life and creating a beautiful environment. The report believes that countries can set their own development goals according to their national conditions, but true development must include improving human health, improving the quality of human life, rationally developing and utilizing natural resources, and creating a development environment that guarantees people's equality, freedom and human rights [69].

(3) Sustainable development defined from a technical perspective. The implementation of scientific and technological progress plays a major role in sustainable development. Without the support of science and technology, there is no way to talk about sustainable development for mankind. Therefore, some scholars have expanded the definition of sustainable development from the perspective of technology selection. For example, Sippers believes that "sustainable development is to move to cleaner and more efficient technologies - as close to zero emission or closed process methods as possible - to reduce the consumption of energy and other resources as much as possible." The World Resources Institute believes that pollution is not an inevitable result of industrial activities, but a manifestation of poor technology and low efficiency. Therefore, their definition is: "Sustainable development is to establish processes or technical systems that produce very little waste and pollutants." According to statistics,

there are more than 70 definitions or interpretations of the concept of sustainable development. Among them, many scholars have defined the concept of sustainable development beyond the general disciplinary attributes. However, at present, the definition of sustainable development given by the World Commission on Environment and Development (WCED) in 1987 is the most accepted and recognized as the classic definition of sustainable development. Its definition is: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [70].

The connotation of sustainable development. Faced with a series of ecological crises such as the increasingly serious population, resource and environmental problems in today's world, human beings have to re-examine the relationship between man and nature. Should we continue to adhere to the traditional development concept or seek to establish a new model of harmonious coexistence and coordinated development between man and nature? At present, establishing the concept of sustainable development has become an important condition for promoting comprehensive sustainable development and a virtuous cycle of economy, society, resources and environment. The main connotation and requirements of the concept of sustainable development include the following.

(1) The concept of sustainable development is a new development concept, which is a negation of the "industrialization realization concept" that simply pursues economic growth. It requires people to re-examine economic growth and economic development with a new perspective and abandon "growth without development". It enables people to realize the importance of coordinated development of economy,

society and environment while paying attention to economic development, and forms a good start for the global sustainable development strategy.

(2) The concept of sustainable development is a development concept that can make the economy, society and ecological environment continue to be coordinated along a healthy track for a long time. Implementing the sustainable development strategy will effectively control population growth, improve people's resource utilization, reduce environmental costs, and enhance the support of resources and environment for long-term development. Moreover, sustainable development requires people to change their traditional attitude towards nature, establish new ethical and moral standards, and achieve harmony between man and nature. This can be said to be a great change in the history of human civilization. In the long run, it will enable human society to develop in a new and high-level way.

(3) The application of the concept of sustainable development to economic analysis has deepened and expanded our understanding of economic theory. The theory of sustainable development has put forward many important concepts such as "natural capital", which correctly and truthfully reflects the actual situation of modern economic operation and is an important development of modern economic theory.

Therefore, the connotation of sustainable development can be understood as the following three aspects: first, needs, which means that the goal of development is to meet human needs; second, constraints, which means that human behavior is constrained by nature; and third, fairness, which refers to fairness between generations, between contemporary people, between humans and other biological populations, and between different countries and regions. These principles are reflected in [71].

Principles of sustainable development.

(1) Fairness Principle. Sustainable development emphasizes that "the satisfaction of human needs and desires is the main goal of development." In economics, fairness refers to the equality of opportunity choice. The principle of fairness pursued by sustainable development includes three meanings: First, intragenerational fairness, that is, horizontal fairness among people of the same generation. Sustainable development must meet the basic needs of all people and give all people the opportunity to meet their desire for a better life. The world must be given fair distribution and fair development rights, and poverty eradication must be a special priority in the process of sustainable development. Second, intergenerational fairness, that is, vertical fairness between generations. The natural resources on which human beings depend for survival are limited. The current generation cannot, because of its own development and needs, damage the conditions for human beings to meet their needs from generation to generation - natural resources and the environment. Future generations must be given the right to use natural resources fairly [72]. Sustainable development must not only achieve fairness among contemporary people, but also between contemporary people and future generations, providing contemporary people and future generations with opportunities to realize their desire for a better life. This is one of the fundamental differences between sustainable development and traditional development models.

(2) Sustainability principle. Mrs. Brundtland discussed the "limitation" factors of sustainable development. Because, without limits, there is no sustainability. "The rate of human exhaustion of natural resources should take into account the criticality of resources". Sustainable development should not damage the natural systems that

support life on Earth: "atmosphere, water, soil, organisms..." Once "development" destroys the material basis of human beings and survival, "development" itself will decline. The core of the principle of sustainability means that human economic and social development cannot exceed the carrying capacity of resources and the environment.

(3) Commonality principle. Although the history, culture and development level of countries in the world are different, sustainable development, as the overall goal of global development, embodies the principles of fairness and sustainability. In addition, to achieve this overall goal, global joint action must be taken. Mrs. Brundtland wrote in the preface of the report "Our Common Future": "Today, our most urgent task may be to convince countries to recognize the necessity of returning to multilateralism" and "further develop common understanding and common sense of responsibility, which is very much needed in this divided world." The principle of commonality is also reflected in the Rio Declaration: "We are committed to reaching international agreements that respect the interests of all parties and protect the global environment and development system, recognizing the integrity and interdependence of our home, the earth." It can be seen that, in a broad sense, the strategy of sustainable development is to promote harmony between humans and between humans and nature. If everyone can consider the impact of this action on other people (including future generations) and the ecological environment when considering and arranging their own actions, and can sincerely act in accordance with the principle of "commonality", then a mutually beneficial symbiotic relationship can be maintained between humans and between humans and nature, and only in this way can sustainable development be achieved.

In short, regarding sustainable development, from the perspective of society, it advocates fair distribution to meet the basic requirements of both the present and future generations; from the perspective of economics, it advocates sustainable economic development based on the protection of the earth's natural system; from the perspective of nature, it advocates harmonious coexistence between man and nature. These views are a challenge to the traditional development model and lay the foundation for mankind to seek a new development model and then form a new development concept.

2.2 Economics of secondary processing

Concept of recycle economy. The recycle economy, as defined in various references, refers to an economic development model that minimizes the input of natural resources into social production, discharges the least waste into the environment, and causes the least harm or damage to the environment through the recycling of resources. The recycle economy is the abbreviation of the closed-loop material flow economy, which is characterized by the cascading and closed-loop recycling of materials and energy. In terms of the environment, it is characterized by low pollution emissions or even zero emissions. The recycle economy integrates clean production, comprehensive resource utilization, ecological design, and sustainable consumption, and uses ecological laws to guide the economic activities of human society. In essence, it is an ecological economy. Its core is to improve the utilization efficiency of the ecological environment and achieve the win-win situation of the environment and economy required by sustainable development through the closed-loop material flow model of "resource consumption-product-renewable resources" [73].

Connotation of recycle economy. There are differences in the definition of the essence and connotation of recycle economy in the academic community. The reason for the difference is that there are different understandings of "resources for circulation" and "circulation methods", which can be roughly divided into "narrow recycle economy" and "broad recycle economy". The concept of "narrow recycle economy" believes that recycle economy develops the economy through the recycling and reuse of waste or waste materials, that is, the economic process of recycling, utilizing, recycling, and reusing various waste materials generated in the process of social production and consumption, and even recycling continuously. "Broad recycle economy" believes that recycle economy is to organize economic activities into a feedback process of "resources-products-renewable resources", so that all resources can be continuously reasonably developed and used in the process, and the adverse impact of economic activities on the natural environment can be reduced to the minimum possible.

It can be seen that the "resources for circulation" referred to by "broad recycle economy" is much broader than that referred to by "narrow recycle economy", and the "circulation methods" are also different. "Narrow recycle economy" emphasizes the recycling and regeneration of waste or waste materials, and is an economic cycle that connects the original open loop of social production. The concept of waste is no longer included in the "broad recycle economy". It emphasizes that all resources should be recycled within the economic system. It not only requires the closing of open-loop social production, which includes the concept of "narrow recycle economy", but also requires the change of the entire social system in accordance with the requirements of recycling resources, including technical support, production organization, lifestyle, social system, ethical and moral concepts, etc., to achieve a dynamic balance of economy, environment and ecology at a higher level. Therefore, the "broad recycle economy" is often also called ecological economy. Simply put, the "narrow recycle economy" is a criticism of people's pursuit of natural resource input and abandonment of waste concepts and practices: while the "broad recycle economy" includes not only the above criticism, but also a comprehensive criticism of the current production mode, lifestyle, way of thinking, etc. Therefore, the two are inherently unified, but the "broad recycle economy" puts forward a deeper concept and a more comprehensive goal of recycle economy.

Principles of recycle economy. The recycle economy takes "reduction, reuse, and resource utilization" as the code of conduct for economic activities, also known as the 3R principle. The principle of reduction (saving resources and reducing waste emissions) is the first principle of the recycle economy. It targets the input end and requires that less raw materials and energy be used to achieve the established production and consumption goals, controlling resource use and reducing pollution emissions at the source of economic activities. The principle of reuse (recycling of materials) belongs to the process method, requiring that products and packaging containers can be reused in their original form many times, rather than being used once, in order to resist the proliferation of disposable products in today's world. The principle of resource utilization (comprehensive reuse of waste) is the output end method, requiring that the produced items can be turned into usable resources instead of useless garbage after completing their use functions, that is, turning waste into resources again to reduce the final disposal volume [74,75].

(1) Principle of saving resources and reducing waste emissions. It is mainly a method targeting the input end, aiming to reduce the amount of materials entering the production and consumption process. In production, manufacturers can save resources and reduce waste emissions by reducing the amount of raw materials used in each

product and redesigning manufacturing processes and procedures. In consumption, people choose items with less packaging and buy durable and recyclable items to reduce the generation of garbage. The core of the reduction principle is to replace end-of-pipe treatment with prevention and whole-process treatment.

(2) The principle of recycling materials. It mainly belongs to the process method, the purpose is to extend the utilization efficiency of products and services, use items as much as possible, avoid items from becoming garbage too early, and pay full attention to the recycling of materials. In production, try to use standard designs so that some equipment can be easily upgraded without having to scrap the entire machine. In consumption, after the product life cycle ends, it is also easy to disassemble and comprehensively utilize so that it can be returned to the market system for others to use or donated to people who need this item.

(3) The principle of comprehensive reuse of waste. It is mainly an output-end method, which reduces the load of end-of-pipe treatment by turning waste into resources again, also known as end-of-pipe treatment. Resourceization can not only reduce the generation of garbage, but also turn waste into treasure and realize the comprehensive reuse of waste. There are usually two ways of resource utilization: one is primary resource utilization, that is, the waste generated by consumers is resourced to form new products that are the same as the original; the other is secondary resource utilization, that is, the waste is turned into new products that are different from the original. In line with this, consumers should also enhance the concept and awareness of consuming recycled products to promote the healthy development of the recycle economy. Since the social and economic system is composed of subsystems at different

levels - enterprise level, regional level, and social level, the recycle economy has three main levels of realization in social and economic activities: clean production at the enterprise level, construction of ecological industrial parks at the regional level, and resource recycling and reuse at the social level. Therefore, the recycle economy system can be constructed from three different dimensions: first, from the dimension of internal circulation of enterprises, develop ecological industries and sustainable agriculture; second, from the dimension of circulation between production, develop ecological industrial chains or ecological industrial parks; third, from the perspective of the overall social cycle, develop green consumer markets and resource recycling industries.

2.3 Analysis of the concept of sustainable development of urban heating networks

The connotation of urban heating. Urban heating is a heating method that uses centralized heat sources to supply heat energy for production or life to heat energy users through facilities such as heating pipe networks. The urban heating system is composed of centralized heat sources, heating pipe networks and other facilities used by heat energy users. It is a form of heating that connects a large number of heat users with heating networks and provides the required heat from a unified heat source [76].

The urban heating system relies on the heat network to connect a large number of heat users, and a unified heat source provides the required heat. The system generally consists of three parts, namely the heat source, the heat network and the heat users; there are four types of heat loads, namely heating load, ventilation and air conditioning load, living heat load and production process load [77]. Central heating, especially cogeneration heating, is of great significance for saving primary energy, improving environmental pollution and improving people's living standards; it also fully demonstrates the convenience, comfort, beauty and safety and reliability of modern cities, and has therefore been widely used in Europe, the United States, Japan and other countries. With the vigorous development of the economy and the rapid improvement of people's living standards, the development prospects of urban central heating will be very broad from the aspects of energy saving, improving people's quality of life, improving urban infrastructure, protecting the environment, and building modern cities.

Factors affecting sustainable development of urban heating.

(1) Heat source. The heat source is the core of the centralized heating system and the main place for energy consumption. The main heat sources for urban heating include thermal power plants, centralized boiler rooms, decentralized boiler rooms, industrial waste heat, geothermal energy and nuclear energy. Since various heat sources have their own advantages and disadvantages and scope of application, the development policy of adapting to local conditions, multiple heat sources and multiple channels has been adhered to in the development of urban centralized heating. These heat source forms are as follows:

First, cogeneration. Cogeneration heating is a form of heating source strongly advocated by China. With the increase in population, the acceleration of industrialization and urbanization, the energy demand will increase significantly, and the energy constraint contradictions and energy and environmental problems faced by economic development will become more prominent. An important aspect of solving the energy constraint problem is to give priority to conservation, take a leapfrog energy-saving path, and build an energy-saving society. From the perspective of sustainable economic and social development, centralized heating by cogeneration is a key area and key project for building an energy-saving society. Compared with separate production of heat and electricity, cogeneration has a 30% higher thermal efficiency, and centralized heating is 50% more efficient than decentralized small boilers. In particular, cogeneration heating is of great significance in saving primary energy, improving environmental pollution, improving heating quality, improving people's living standards, and increasing electricity supply. It also fully demonstrates the convenience, comfort, aesthetics and safety and reliability of modern cities, and has therefore been widely used in Europe, the United States, Japan and other countries.

Second, boiler room heating. The most commonly used form of heating source in China is boiler room heating. China currently has more than 400,000 small industrial boilers, with an average single capacity of 2.3T/h and a total capacity of about 900,000T/h, accounting for more than 90% of the total industrial consumption. In the heating area of civil buildings in large cities in the heating area, the heating of the boiler room of the housing management system accounts for more than 80% of the total building area. However, the operating boiler has a small single capacity, low load rate, low thermal efficiency and high energy consumption. In recent years, boiler room heating has made great progress, but it also faces a severe situation. For example, when formulating urban heating plans, the overall planning of boiler room heating is not given enough attention. Due to problems such as the system and funding sources, the phenomenon of repeated construction of dispersed boiler rooms often occurs. Although great progress has been made in the design and manufacture of boiler equipment, such as 14, 28, and 35MW large hot water boilers have been mass-produced, there is a lack of supporting products for large hot water boilers and their auxiliary machines. The operation and management level is generally low, and heating management personnel lack the necessary management knowledge and professional skills.

Third, industrial waste heat, geothermal energy, nuclear energy and other heat sources. The state supports cities in developing urban centralized heating using industrial waste heat and geothermal energy. Among them, geothermal heating has been hindered by low water temperature and corrosion. The state has listed nuclear energy heating as a national scientific research project and has achieved results. At present, there are special heating tests and trials, but it cannot be promoted in large quantities due to funding constraints.

(2) Heating network. The heating network is the link between heat sources and heat users, and plays the role of transporting and distributing heat sources. The heating pipe networks in most cities in China generally have problems such as water seepage in the pipe trenches, large heat losses, and high water loss rates; most of the direct buried pipes are handmade, and the design and installation specifications and regulations for direct buried insulation pipes have not yet been formulated, and there are no ideal steam direct buried pipes; many small and medium-sized cities still use low-temperature and high-flow operation methods, which increases operating costs; the heating network regulation is relatively simple, the thermal and hydraulic conditions are out of balance, the heating station functions are simple, and the regulation methods are backward. In recent years, China has built steam pipe networks or hot water pipe networks in 158 cities, gradually changing the previous single branch pipe network system form, and designing and applying the multi-heat source combined

heating system form; in terms of the structure of the heat network, the direct burial laying method has been applied to the hot water heating pipeline, and the pipe trench laying technology has also made great achievements; in the connection method between the hot water network and the user, especially in the system with a large heating area, the indirect connection form is applied, changing the traditional direct connection method; in terms of the regulation of the heat network, the regulation method and automatic control technology of the heat network have been developed, changing the past regulation method of not using any regulation means or single regulation, and developing a microcomputer monitoring system for the regulation means, using balancing valve intelligent instruments and self-powered flow, pressure difference and temperature regulators; in terms of technical application, new technologies, new equipment and production lines related to the heat network have been introduced, the level of heat network design has been improved, the scientific research work of the heat supply system has been promoted, and a new situation has emerged in the management of heat supply enterprises.

(3) Heat users. Heat users are heat consumers and heat beneficiaries. Heat directly corresponds to heat users. The most important thing about heat supply is to satisfy users. Heat users are consumers of "heat", with a large number and wide distribution. Chinese urban heating users are basically heating users. For building heating, the purpose is to meet the thermal comfort requirements of users so that they are not disturbed by changes in outdoor temperature. Different users have different requirements for comfort. Even the same person has different requirements for comfort in the same environment. To meet the different thermal requirements of different users,

the best way is to provide users with means to adjust the room temperature so that users can control their thermal comfort. Many countries are still unable to do this, but the purpose of heating is to meet the thermal needs of the majority of users and make them feel satisfied. For the satisfaction of users, this is a direction to strive for.

(4) Resources. Resources are the public property of a country or region, facing the problem of management and equal use rights. The use of resources has a dual effect on social economy and ecological environment. It can not only promote social and economic development, but also inevitably bring different degrees of impact on the ecological environment. The demand for resources in countries around the world continues to increase, the growth rate of resource consumption is accelerating, and the degree of environmental pollution is intensifying. However, the supply of energy and mineral resources in the world is not only limited but also very unstable. Some natural resources are non-renewable resources; some are renewable resources, but if they are not consumed reasonably, they will cause resource depletion. Therefore, while we use natural resources, we also face the responsibility of protecting natural resources. Reasonable use of various natural resources can not only promote social and economic development to the greatest extent, but also minimize the adverse impact on the ecological environment. Only by using natural resources equally, improving resource utilization efficiency, and protecting non-renewable natural resources can we maintain the sustainable development of society. Resources include energy, water, forests, land, etc. The main energy sources used in urban heating in China are coal, oil, natural gas, etc. Although China has relatively rich coal resources, its oil and natural gas resources are relatively scarce. In the long run, the domestic energy supply will face a potential total shortage,

especially the structural shortage of oil and natural gas supply. Therefore, the analysis of energy is an important part of studying the sustainable development of urban heating.

(5) Environment. Humans are inseparable from the natural environment. Humans are both the product of the environment and the transformer of the environment. In recent decades, the urban heating industry has developed rapidly, but the ecological environment has suffered the most serious pollution and damage in history. The deterioration of the environment has not only become the most important factor restricting economic development, but also threatens human survival. In recent years, although the investment in environmental protection and governance has been increased, the pace of environmental pollution control and ecological construction has accelerated, and the environmental quality of some cities and regions has improved significantly. However, the intensity of environmental governance is far behind the speed of destruction, the overall ecological environment continues to deteriorate, and the environmental pollution situation is becoming increasingly serious. The environmental pollution caused by heating is mainly manifested in: the groundwater level drops, the water pollution increases; the air pollution is serious; the amount of solid waste stored is too large, and urban pollution spreads to rural areas. If the environmental situation is allowed to develop in this way, it will inevitably have a huge negative impact on the economy and society. Urban heating is part of the city's large system, which will have a great impact on the environment. Heating is a major issue related to the food and clothing of a city's citizens. To ensure heating, we must respect the characteristics of a city's energy structure and be consistent with the policy of energy conservation. The sustainable development of heating must also meet the

requirements of environmental protection. In the process of heating, a large amount of exhaust gas and waste will cause great damage to the environment. In the sustainable development of urban heating, the impact on the environment must be taken into account. It is necessary to maintain the sustainable development of the heating industry while protecting the ecological environment.

(6) Technology. China's urban heating system originally adopted traditional methods in terms of technology. However, with the continuous expansion of technical exchanges and cooperation with foreign counterparts, some advanced technologies, materials, processes and equipment related to heating have been gradually introduced, which has improved the level of heating design, promoted the scientific research of heating systems, and brought about a new situation in the management of heating enterprises. For example, in terms of new technologies: on the basis of introducing and absorbing foreign designs, various design software related to urban heating systems are selected and promoted, and CAD-assisted design systems are promoted and applied; in terms of new processes: shallow burial and dark excavation processes are promoted; factory prefabrication of thermal pipelines and components is developed, construction and installation processes are simplified, and interface process equipment for direct burial of prefabricated insulated pipelines is developed; in terms of new equipment: various typical models of heating network dispatching automation equipment and measurement and control management equipment for thermal stations are established and promoted: variable speed pumps, self-powered flow, differential pressure, temperature regulating valves, bellows compensators, etc.; in terms of new materials: prefabricated direct burial pipelines, etc.

(7) Implementation price. Price phenomenon is one of the most common phenomena in social practice, and price level is the most informative indicator discovered so far. It is the result of the interaction and comprehensive movement within and between social systems, economic systems, and natural environment systems. Price is the lever of the economy. In the market economy, commodification and pricing are the process of people's understanding and processing of "material value" from macro to micro, from rough to fine, from shallow to deep, and from theory to practice. Commodification and pricing are an inseparable whole in the market economy. Undoubtedly, the commodification and pricing of heat are the basis and guarantee of heat economization. When setting heat prices, the rationality and standardization of heat prices must be ensured. The main purpose of heat economization is to achieve the sustainable development of heat itself to meet the requirements of human society for sustainable development. Heating companies provide heat to heat users, so there is a heat price. Many places adopt heat metering and charging. There are two problems in metering and charging. Almost all heating companies adopt a flat-rate charging method, that is, charging users according to the building area provided for heating. However, the prices in many areas are too low and deviate from the heat price. The heating department is faced with the problem of setting a reasonable price that heat users can accept. Therefore, the price issue is an important factor that must be considered in the study of sustainable development of urban heating.

The relationship between various influencing factors in the traditional development mode of urban heating. The history of human economic and social development is a history of the development of the relationship between man and nature. Our attitude towards nature will determine our future. Human beings have a profound understanding of this issue from the reflection on the ecological and economic crisis in recent decades. Under certain conditions, there is a certain substitution relationship between economic development and ecological resources and environment. To achieve a faster economic development speed, it is necessary to sacrifice the quality of the ecological environment. If the ecological environment is to be protected and improved to a higher degree, it must be at the cost of a proper reduction in the speed of economic development. However, this substitution has certain limits, especially when the quality of the ecological environment drops to a certain extent, the deterioration of the ecological environment will not only fail to continue to exchange for economic development, but will also seriously hinder economic development. The ecological environment is the natural foundation of economic development. When it is damaged to a certain extent, economic development will be curbed due to the destruction of the development foundation. At this time, economic development must be based on the quality of the ecological environment. So in a sense, economic development and the ecological environment have a positive proportional relationship.

The traditional economy is a linear economy with a one-way flow of "resources-products-pollution emissions", which is characterized by high exploitation, low utilization and high emissions. People extract materials and energy from the earth at a high intensity, and then discharge a large amount of pollution and waste into the water system, air and soil. The utilization of resources is extensive and one-time. The quantitative growth of the economy is achieved by continuously turning resources into waste. It leads to the shortage and depletion of natural resources and causes catastrophic environmental pollution. The relationship between the various influencing factors in the traditional development mode of urban heating can be represented by Fig. 2.1 and Fig. 2.2.

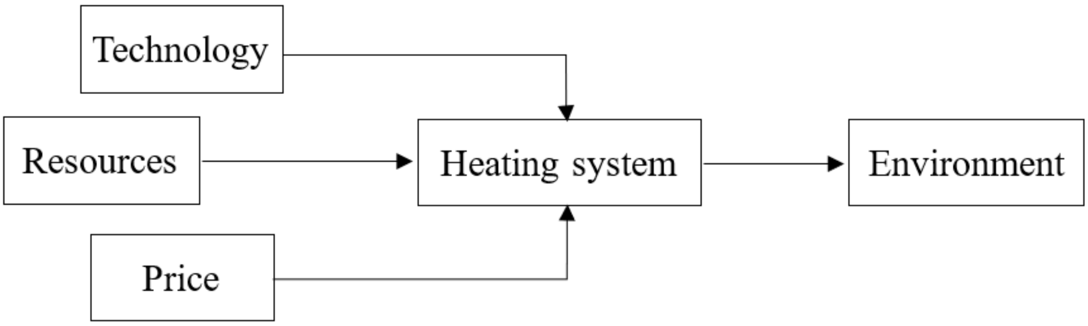

Fig. 2.1 – 1st relationship of factors of traditional development of heat supply in cities

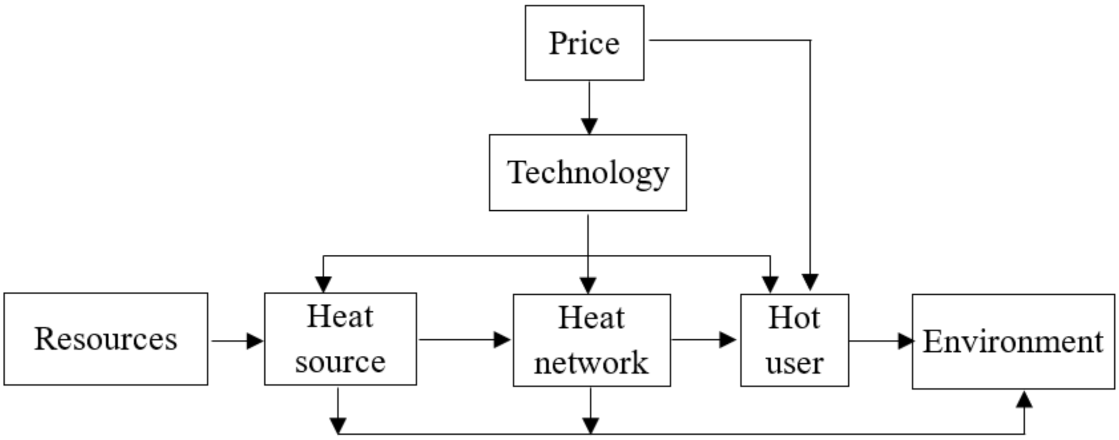

Fig. 2.2 – 2nd relationship of factors of traditional development of heat supply in cities

It is not difficult to see from the above two figures that although the traditional development mode of urban heating in China has achieved the transformation of input and output, it has not yet stepped out of the resource-based model, with high input, high consumption, low efficiency and low output. It pursues the growth of output value and ignores the improvement of quality. Technology is simply used as a tool for input and output and material conversion, resulting in a lack of stamina in the macro economy.

Taking all factors into consideration, sustainable development requires urban heating to change from the traditional development model that simply pursues quantity increase to a sustainable development model that focuses on development quality and the welfare of future generations. This requires us to change the traditional production and consumption model characterized by "high input, high consumption and high pollution" and implement clean production, civilized consumption and civilized life, which is necessary for human development.

Application of recycle economy theory in sustainable development of urban heat supply. Recycle economy is a kind of ecological economy in essence. According to its basic ideas, namely Reduce, Reuse and Recycle, it can effectively recycle resources, improve the utilization rate of resources, minimize the emission of pollutants, and realize the win-win goal of sustainable economic development and effective environmental protection. By applying the theory of recycle economy to the study of sustainable development of urban heat supply, we can re-understand the relationship between various influencing factors in the development mode of urban heat supply, as shown in Fig.2.3 and Fig.2.4.

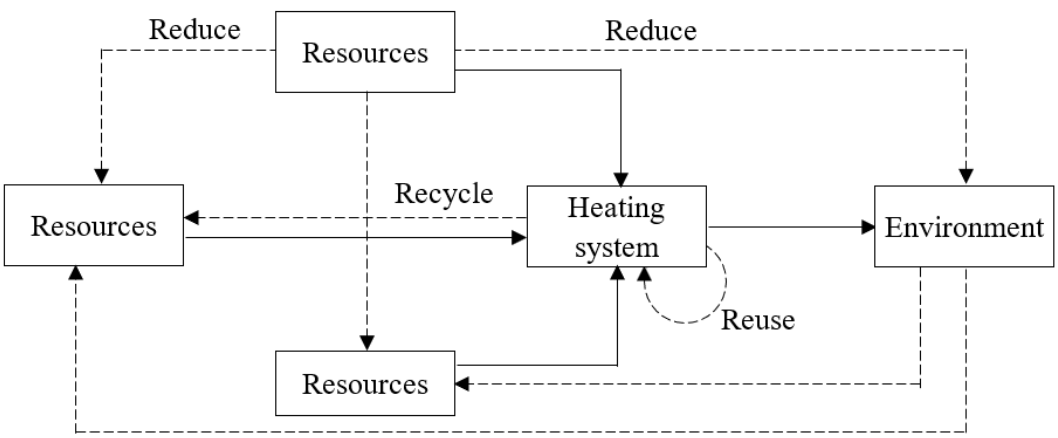

Fig. 2.3 – 1st Recycle economy mode of sustainable development of heat supply in cities

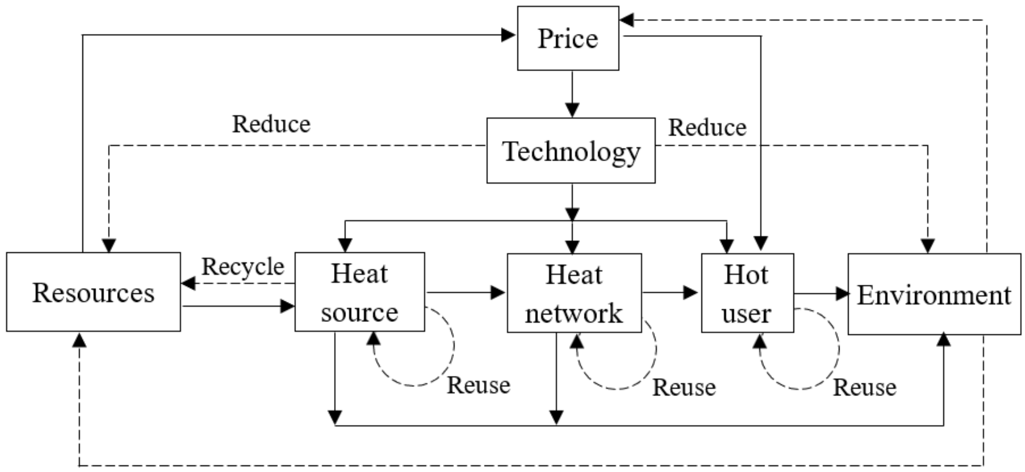

Fig. 2.4 – 2nd Recycle economy mode of sustainable development of heat supply in cities

Recycle economy is a new model of sustainable development that is friendly to the earth and friendly to the earth. It fully considers the carrying capacity and purification capacity of the nature, follows the "producer-consumer-decomposer" circulation path and food chain network in the ecosystem, and makes the organization of human economic activities into a closed loop process of "resource-product-consumption-renewable resources" repeated circulation of resources. All raw materials and energy in the continuous economic cycle to get the most reasonable use, so that human activities on the natural environment to control the negative impact of the extent as little as possible, in order to achieve low exploitation, low input, low emissions, high utilization of resources.

2.4 An improved method for the rational implementation of energy-saving technologies in the field of heat supply

In the process of urbanization, energy-saving and environmental protection technologies in heating systems are an important way to achieve sustainable development.

In recent years, as the problem of global climate change has intensified, many cities have begun to take active energy-saving measures to reduce greenhouse gas emissions and improve energy efficiency. Many cities in Ukraine (such as Kiev, Kharkiv, Lviv, etc.) have pledged to reduce greenhouse gas emissions by 30% by 2030 by joining the Mayors Climate and Energy Pact [78]. The realization of this goal depends on the rational implementation of energy-saving and environmental protection technologies in heating systems.

Comprehensive benefits of energy-saving and environmentally friendly technologies and the rationality of their implementation. The results of the analysis of current trends in the development of the heat supply sector in different countries show that the rational implementation of energy-saving and environmental technologies can not only significantly reduce thermal energy consumption and greenhouse gas emissions, but also bring significant economic benefits. Appendix B provides a justification for the rational implementation of energy-saving technologies in the field of heat supply. By using a multi-criteria evaluation method, reference [79] comprehensively analyzed the comprehensive benefits of intelligent control technology and solar thermal collectors in heating systems. The successful application of these technologies has provided valuable experience for other cities, especially in the following aspects:: *multi-dimensional evaluation:* Through a comprehensive evaluation of the three dimensions of energy, environment and economy, the scientific nature and feasibility of energy-saving measures are ensured; *dynamic control:* Dynamic adjustment of heating systems can be achieved through intelligent control systems to avoid energy waste; *renewable energy utilization:* Reducing dependence on traditional fuels through renewable energy technologies such as solar thermal collectors. In short, the rational implementation of energy-saving and environmental protection technologies is the key to achieving sustainable development of urban heating systems. By introducing intelligent control technologies and renewable energy technologies, cities can maximize economic benefits while reducing energy consumption and environmental pollution.

Other energy-saving and environmental protection technologies. With the development of social economy and the improvement of living standards, people are consuming more and more energy while pursuing a more comfortable living environment. According to references [82,83], in developed countries, building energy consumption accounts for about 40% of total energy consumption. In China, this proportion is about 25%, ranking first among all energy consumption, of which more than 50% is consumed in winter heating and summer cooling and air conditioning. As the energy supply tension in the world becomes increasingly severe, energy will become the main factor restricting the economy of various countries. As a major energy consumer, the construction industry has great energy-saving potential. Vigorously developing and promoting new building energy-saving technologies such as solar photovoltaic technology, ground source heat pump technology, solar collector and air source heat pump combined heating, etc., while continuously improving people's living environment comfort, reducing the total energy consumption of buildings, and effectively alleviating the contradiction between energy supply and demand, has both practical economic significance and important social significance and environmental value.

(1) Solar photovoltaic technology. As a clean and renewable energy source, solar energy is gaining more and more attention and its application fields are becoming more and more extensive. According to statistics, more than 60% of China's land area has an annual sunshine time of more than 2,200 hours and an annual total radiation of more

than 5.02 million kJ/m^2, which has created abundant resources and favorable conditions for the use of solar energy. According to the characteristics of solar energy and the needs of actual applications, its current application in building energy conservation can be divided into two forms: photovoltaic conversion and photothermal conversion.

Solar photovoltaic technology refers to the use of solar cells to convert solar energy during the day into electrical energy, which is stored in batteries and released at night under the control of a discharge controller for indoor lighting and other needs.

The solar photovoltaic conversion system is mainly composed of solar cells, charge and discharge controllers, batteries, loads, etc. Among them, the photovoltaic cell assembly is composed of multiple single-crystal silicon or polycrystalline silicon cells connected in series and parallel, and its main function is to convert light energy into electrical energy; the charge and discharge controller is mainly used to control the charging and discharging of the battery, and has reverse discharge protection function and polarity reverse circuit protection function, and can also realize the monitoring and data collection of the system; the battery is the energy storage device of the system, and its main function is to store the electricity generated by the solar cell and provide energy when the user needs it.

(2) Ground source heat pump technology. In the application of building energy conservation, ground source heat pump technology, as an important technology for the implementation of energy conservation and environmental protection, has been continuously improved and widely used. In the implementation process of ground source heat pump technology, its energy-saving effect is mainly reflected in different seasons. In the summer, the system can operate through its own equipment, convert and store the indoor heat into the ground structure, and meet the summer cooling needs.

When the winter heating season comes, professional equipment should be used to effectively extract the heat stored in the summer, and finally meet the winter user heating needs. The most obvious technical advantage and feature of ground-source heat pump technology is that during the operation of the technology, the electricity consumption is lower than that of traditional heating modes. For every unit of electricity consumed by ground-source heat pump equipment, 3 to 5 units of heat energy can be effectively produced. Generally, during the actual operation of the ground-source heat pump system, for every 1 kW of energy invested, the user can obtain more than 4 kW of heat and cooling materials [84]. Therefore, the promotion and application of ground-source heat pump technology can effectively improve energy utilization while achieving the goal of energy conservation and environmental protection.

Based on a detailed analysis of the current construction status, it is generally believed that ground source heat pump technology has the advantage of saving energy, can be widely used in ordinary residential and public buildings, and is economical and practical with good operating results [85].

(3) Solar collector and air source heat pump combined heating technology. Since the beginning of this century, energy shortages and environmental pollution have become increasingly serious. According to the 2017 World Energy Statistics Yearbook report [86], the proportion of renewable energy power generation in 2017 increased by 14.1% compared with previous years, of which solar energy contributed about one-third of the growth. Air source heat pumps consume electricity, absorb energy from low-temperature environments, and release energy in high-temperature environments to complete heating. The concept of combined operation of solar energy and heat pumps

was first proposed by Jordan in the 1950s [87]. After that, scientific researchers conducted research on this and designed different types of solar heat pump systems. Solar heat pumps combine the two to complement each other's advantages; this can improve the overall heating performance of the system. Solar heating and air source heat pumps are currently two important energy-saving technologies, but due to their own defects, the application of either alone cannot meet the heating needs well. Therefore, the combined operation of the two is currently the main research content.

China has a vast territory, mainly in the temperate and subtropical zones, and has abundant solar energy resources. The distribution shows a decreasing trend from west to east. This is because the western plateau of China is at a high altitude, with thin air and strong solar radiation. The total annual solar radiation in different regions ranges from 3300 – 8000 MJ/m^2, with an average value of 5900 MJ/m^2 [88]. Although solar energy resources have the advantages of being clean, environmentally friendly and renewable, they also have the disadvantages of being discontinuous and unstable, so auxiliary energy is needed to ensure stable heating. In addition, if solar heating systems are used in large buildings, the initial investment in equipment will be greatly increased. In order to overcome the above problems and improve energy utilization, heat pump technology stands out among many technologies due to its high efficiency and environmental protection advantages. At present, solar heat pump technology, which combines the advantages of solar energy and heat pump technology, has been widely used.

The solar heat pump system is a combination of solar collectors and heat pumps. It has the advantages of both and overcomes the problems of their separate operation, making this technology receive widespread attention.

At the same time, the solar heat pump system still has some imperfections that need to be further studied. For example, in the current experiments, a fixed flow system is mostly used, and the circulating water pump and the heat pump unit are both operated at the maximum flow, resulting in a waste of electricity. In the future, research can be strengthened on system frequency conversion control so that the flow of the heat collection system can be adjusted according to the heat.

At present, many countries are in a period of rapid urbanization and industrialization. The total amount of existing buildings and the annual new building area are very large, but the proportion that can meet the building energy-saving standards is very low, resulting in a huge waste of energy, but the energy-saving potential is also great. Therefore, actively developing and vigorously promoting new building energy-saving technologies, reducing the level of building energy consumption while improving people's living environment, and building a conservation-oriented society are of great practical significance and long-term social significance for maintaining the sustainable development of the national economy and alleviating the contradiction between energy supply and demand. Therefore, the development and application of new technologies, new energy and new materials such as solar photovoltaic technology, ground source heat pump technology, solar collector and air source heat pump combined heating have broad development prospects.

Improve the methods of rationally implementing energy-saving technologies in the field of heat supply. The rational implementation of energy-saving technologies (RIEST) is a method to improve the efficiency of greening in urban areas by rationally implementing recommended energy-saving technologies and using the resulting economic effects, by reducing investment costs, in order to realize the ecological and economic potential of objects in the field of heat supply. The shows a schematic diagram of the RIEST method, which reveals its essence (Fig. 2.5).

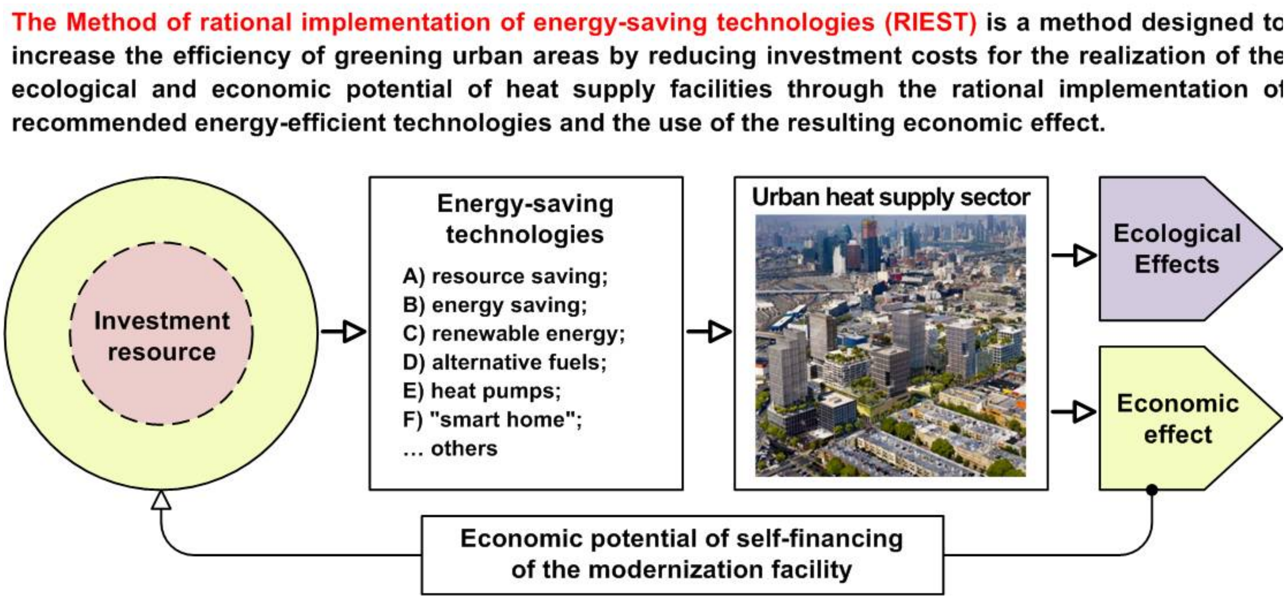

Fig. 2.5 – The essence of the RIEST method in the field of heat supply

This diagram represents several fragments logically connected to each other.

The sphere of urban heat supply is presented as an object of implementation of a complex of energy-efficient technologies that increase its environmental and economic efficiency. To implement this set of technologies, an investment resource is required (shown as a multi-colored circle on the left), which, according to the RIEST method, is proposed to be formed from 2 sources: direct investment (marked in red in the diagram) and the self-financing potential of the research object (marked in yellow in the diagram). This approach allows you to obtain the following advantages compared to the strategy of simultaneous comprehensive implementation of all recommended technologies with full 100% financing of this process: 1) the amount of investment required for energy modernization of the research object is reduced, 2) the specific cost of the obtained environmental effects is reduced, 3) the financial flow of saved funds as a result of reducing excess heat losses is converted into an additional investment resource. The main theoretical provisions of the RIEST method are presented in works [89,90].

Fig. 2.5 systematically illustrates the mechanism of the RIEST approach, highlighting the diverse applications of energy-saving technologies in the field of urban heat supply and the dual benefits they bring. As can be seen from the figure, there is a set of energy-saving technologies that can be implemented into the required investment. This technology is applied in the field of urban heating. The figure lists six energy-saving technologies, namely resource saving, energy saving, renewable energy, alternative fuels, heat pumps, and "smart home". By integrating technologies such as resource saving and renewable energy, not only can the investment cost be reduced, but also a virtuous cycle of ecological protection and economic benefits can be achieved. In addition, the "economic potential of self-financing of the modernization facility" emphasized in the figure further shows that the approach is sustainable and scalable. We suggest improving this process from technologies that affect economic effects, which will reduce investment. Therefore, our approach can use the obtained effects to reduce the cost of implementing such technologies, providing a practical path for the green transformation of cities.

The method of rational implementation of energy-saving technologies in the field of heat supply has been improved by introducing new ecological and economic criteria for assessing the effectiveness of energy modernization procedures for technical systems "producer-consumer of thermal energy", the introduction of which allows for a more complete assessment of the degree of rationality of the use of investment resources when carrying out energy-efficient measures and implementing programs to improve the energy and environmental security of urbanized areas. (Fig. 2.6).

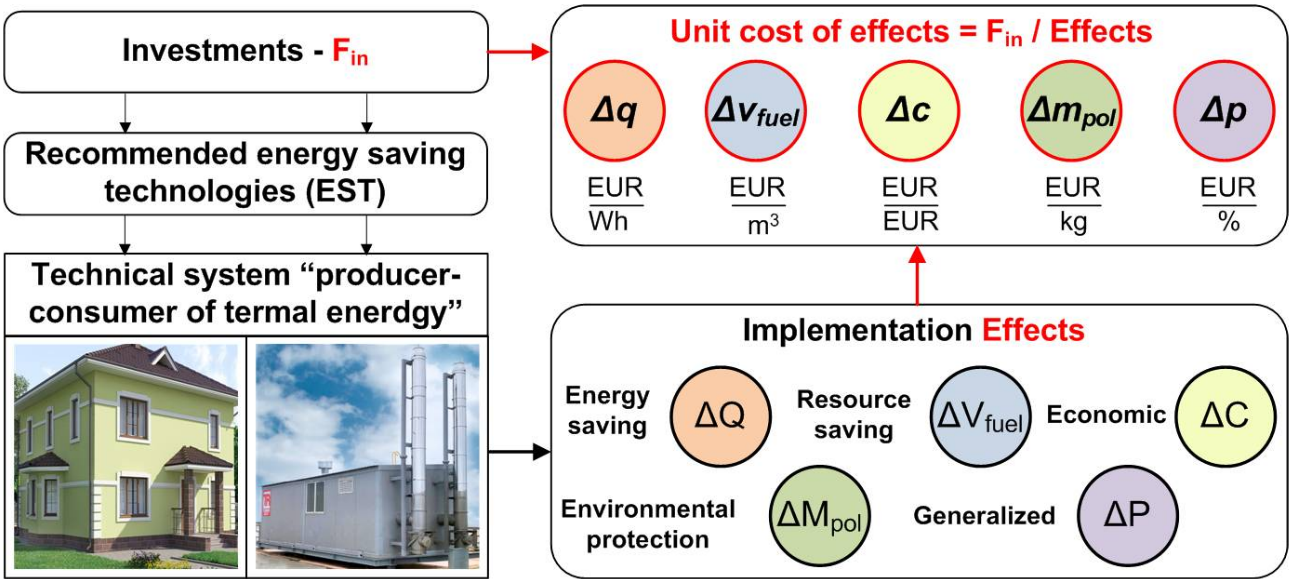

Fig. 2.6 – Schematic diagram of the improved RIEST method

This figure shows a schematic diagram of the improved RIEST method, which consists of the main logically interconnected fragments with these connections indicated by arrows. The diagram shows the technical complex "producer-consumer of thermal energy", which is buildings with heat supply systems, considered as a single whole. As a result of the implementation of recommended (according to the results of the energy audit of this technical complex) energy-saving technologies, the main effects are achieved, indicated in capital letters:

ΔQ – energy saving effect: thermal energy savings, Wh;

ΔV_{fuel} – resource-saving effect: saving fuel (natural gas), m^3;

ΔM_{pol} – reduction of harmful pollutant emissions, kg;

ΔC – saving of economic costs for heat supply of buildings, EUR;

ΔP – dimensionless generalized ecological and economic effect, %.

The essence of the improvements to the RIEST method is marked in red in the diagram (text and arrows-connections). New criteria for assessing the effectiveness of EST implementation have been introduced, which are the specific costs of the obtained effects (indicated by lowercase letters), which are determined as the result of dividing the volume of direct investment required to obtain the corresponding effect – F_{in} by the effect itself:

Δq – specific cost of energy saving effect, EUR/Wh;

Δv_{fuel} – specific cost of resource-saving effect, EUR/m^3;

Δm_{pol} – specific cost of ecological effect, EUR/kg;

Δc – specific cost of economic effect, EUR/EUR;

Δp – specific cost of the generalized ecological and economic effect, EUR/%.

This representation method can more intuitively reflect the effect we have obtained - the cost saved after implementing energy-saving technology. By quantifying these indicators, this method comprehensively evaluates the comprehensive benefits of the technology in terms of energy, resources, environment and economy, and provides clear data support for technology application and decision-making.

Overall, this schematic diagram intuitively presents the improvement effect of the RIEST method through systematic indicator design, highlights its advantages in energy saving and consumption reduction, environmental protection and emission reduction, and economy, and has strong practicality and reference value.

Improving the mathematical model of the efficiency of the rationalization implementation process. A mathematical model for determining the parameters and assessing the effectiveness of procedures for the rational implementation of energy-saving technologies was further developed, which took into account the losses of the integral energy-saving potential of objects that produce and consume thermal energy in the initial and final periods of its phased implementation; this allows increasing the accuracy of this mathematical model and the reliability of the environmental and economic effects established on its basis.

The Fig. 2.7-2.10 respectively presents the main theoretical provisions of the improved RIEST method in the form of 4 graphic fragments arranged in accordance with the research algorithm that is performed when implementing this method.

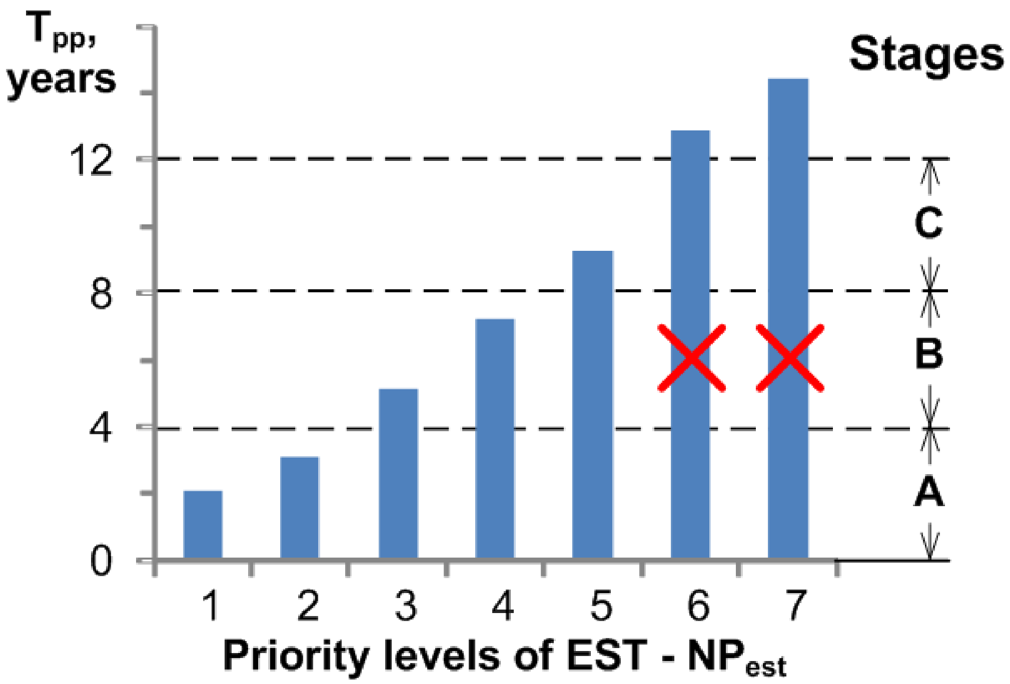

Fig. 2.7 – Distribution by stages recommended for implementation of EST

The Fig. 2.7 demonstrates the 1st part of such studies – determining the priority levels – NP_{est} recommended for the implementation of energy-saving technologies and their distribution in 3 stages:

Stage A – the first quick-payback stage with a payback period of up to 4 years (higher priority is given to technologies with a shorter payback period T_{pp});

Stage B – the second medium-payback stage with a payback period of 4 to 8 years;

Stage C – the third long-term payback stage with a payback period of 8 to 12 years.

Technologies that have payback periods longer than 12 years are considered unprofitable and are not considered when implementing the RIEST method.

This figure uses the payback period (T_{pp}) as the core indicator to prioritize and stage the implementation of energy-saving technologies (EST). The horizontal axis represents the priority of energy-saving measures, arranged from short to long according to the payback period. The vertical axis represents the payback period (T_{pp}) of different measures.

By prioritizing the implementation of stage A (rapid recovery) measures, early capital return is ensured to provide financial support for subsequent stage (B and C). Phased implementation (A→B→C) reduces financial risks and avoids the break of the capital chain due to long-term high investment. This figure clarifies the implementation order through scientific classification, ensures efficient use of funds, and reserves space for future technology upgrades, reflecting the optimization logic of the RIEST method in balancing short-term benefits and long-term sustainability.

Fig. 2.8 shows the second part of the research, is devoted to determining the annual economic effects of the stages - ΔC_A, ΔC_B, ΔC_C, the total economic effect ΔC, the payback periods of the stages - T_{ppA}, T_{ppB}, T_{ppC} and strategy 1 - T_{pp1} and the estimated values of the investment volume values of the stages - $F_{in(est)A}$, $F_{in(est)B}$, $F_{in(est)C}$ and strategy 1 - $F_{in(est)1}$ (the actual value of the investment volume of strategy 1 – $F_{in(act)1}$ and the calculated value – $F_{in(est)1}$are equal).

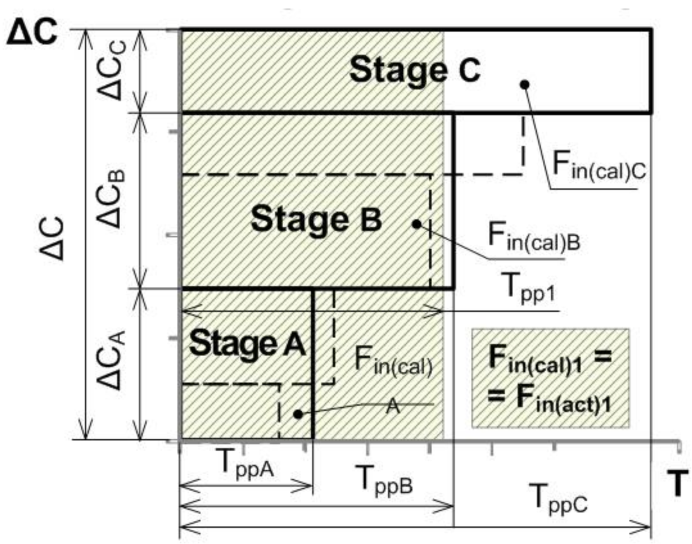

Fig. 2.8 – Determining the durations and costs of the stages of RIEST strategies

The core advantage of this method lies in the continuity of the capital chain between stages - the economic benefits generated in the previous stage can directly support the investment in the subsequent stage, forming a self-sustaining financing cycle. At the same time, the progressive implementation logic of sorting technologies by the length of the payback period (short → medium → long) in stages not only ensures the rapid return of early funds, but also reserves space for long-term technology deployment, reflecting the innovative design of the RIEST method in optimizing capital liquidity and technical synergy.

The third part of the research, presented in the Fig. 2.9 (a), is devoted to determining the parameters of the studied EST implementation strategies, which are the delay periods of stages A, B and C – ΔT_A, ΔT_B, ΔT_C. In this case, stage A is always performed without delay ($\Delta T_A = 0$), and stages B and C can be performed with delays of 0, 1 or 2 years. Thus, the possibility of implementing 9 RIEST strategies with different combinations of delay periods for the execution of stages B and C is considered. The effectiveness of these strategies is also compared with the current state of the research object, which corresponds to strategy 0, for which the delay periods for the execution of stages are unlimited.

RIEST Strategy	Delay periods for the start of stage, years		
	ΔT_A	ΔT_B	ΔT_C
0	∞		
1			0
2	0	0	1
3			2
4			0
5	0	1	1
6			2
7			0
8	0	2	1
9			2

a)

Financial flows to implement strategies
Excess costs for heat supply: $F_{lost} = \Delta T_B \times (\Delta C_B + \Delta C_C) + \Delta T_C \times \Delta C_C$
Saved financial resources: $F_{save} = \Delta C \times (\Delta T_B + \Delta T_C) - F_{lost}$
Additional financial resource: $\Delta F = F_{save} - F_{lost}$
Actual investment volume: $F_{in(act)} = F_{in(cal)} - \Delta F$
Relative savings of investments: $\delta F_{in(act)} = (1 - F_{in(act)} / F_{in(cal)}) \times 100\ \%$

b)

Fig. 2.9 – Development of a mathematical model for determining parameters and evaluating the effectiveness of RIEST strategies 1

Fig. 2.9 (b) of this block of research contains information on the financial flows that make up the actual investment volume of the strategies under study, which are:

F_{lost} – excessive financial costs for heating the RO, EUR, shown in pink;

F_{save} – saved financial resources from the implementation of EST, EUR, shown in yellow;

ΔF – self-financing resource of the RO, EUR;

δF – relative saving of investment costs, %.

The table also contains formulas for determining these financial flows.

The presented Fig. 2.10 shows an example of a graphic representation of strategy 6, which is characterized by the following parameters: $\Delta T_A = 0$, $\Delta T_B = 1$ year, $\Delta T_C = 2$ years.

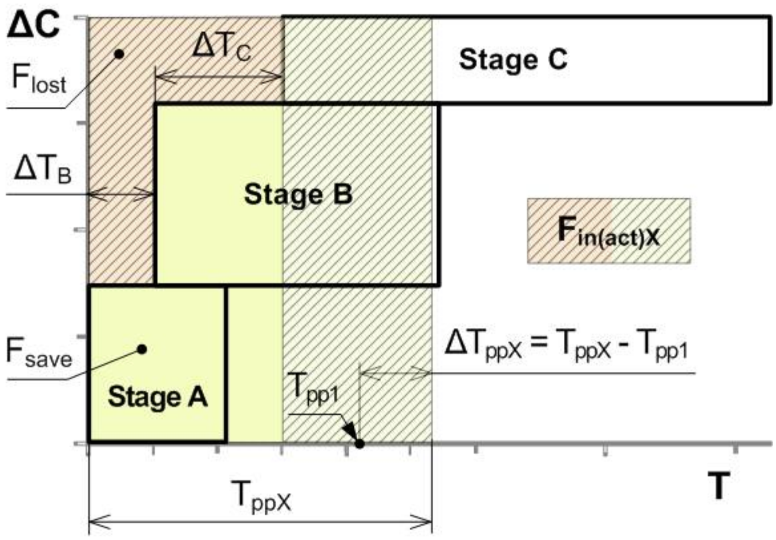

Fig. 2.10 – Development of a mathematical model for determining parameters and evaluatingthe effectiveness of RIEST strategies 1

Provide information basis for the rational implementation of energy-saving technologies. For the first time, the feasibility of using and developing an information map form for multi-criteria assessment of the effectiveness of various strategies for the rational implementation of environmental energy-saving technologies based on the criteria of the specific cost of achieved environmental, economic and generalized effects has been scientifically substantiated, which constitutes an information basis for making reasoned technical decisions regarding the choice of the most cost-effective procedures for realizing the energy-saving potential of buildings and heat supply systems. Tables 2.1-2.4 constitute the Information card on the effectiveness of strategies for the rational implementation of energy-saving technologies.

Table 2.1 presents the results of the assessment of the current technical, energy and environmental state of the research object – the technical complex "producer-consumer of thermal energy" or its elements - buildings, heat supply systems.

Table 2.1 – Current energy and environmental status of the research object

S_{ha},	Q,	Q_s,	V_{fuel},	M_{CO2},	M_{NOx},	C_{heat},	
m^2	MWh	kWh/m^2	thou. m^3	tone	kg	ths.UAH	ths. EUR

These data provide benchmarks for evaluating energy saving potential. The current state of this object is characterized by the following parameters:

S_{ha} – total heated area of the building, m^2;

Q – annual thermal energy requirement of the building, Wh;

Q_S – specific annual thermal energy demand of a building, Wh/m^2;

V_{fuel} – annual fuel (natural gas) requirement of the RO, m^3;

M_{pol} – annual mass emission of harmful pollutants into the atmosphere, kg;

C – annual economic costs for heat supply of the, EUR.

By quantifying the energy and environmental status quo of the research object, the table lays the foundation for evaluating the effect of the implementation of energy-saving technologies.

Table 2.2 presents the results of the assessment of the energy saving potential of the research object, which is determined as a result of an energy audit and is characterized by the following parameters:

ΔQ – energy saving effect: thermal energy savings, Wh;

ΔQ_S – specific energy saving effect, Wh/ m^2;

ΔV_{fuel} – resource-saving effect: saving fuel (natural gas), m^3;

ΔM_{pol} – reduction of harmful pollutant emissions, kg;

ΔC – saving of economic costs for heat supply of buildings, EUR;

ΔP – dimensionless generalized ecological and economic effect, %.

Table 2.2 – Energy efficiency potential of the object under study

δP,	ΔQ,	ΔQ_s,	ΔV_{fuel},	ΔM_{CO2},	ΔM_{NOx},	ΔC,	
%	MWh	kWh/m^2	ths. m^3	tone	kg	ths.UAH	ths. EUR

These indicators are presented in the form of percentages, so that energy-saving potential can be evaluated from many angles. By comparing the current state with the potential effect, the improvement space of energy-saving technology has been clarified.

Table 2.3 presents the results of the assessment of efficiency indicators, payback periods – T_{pp} and estimated cost – $F_{in(est)}$ of each energy-saving EST recommended for implementation and each stage – A, B, C (which consist of groups of technologies distributed according to the values of their payback periods). The table evaluates the effect of energy-saving technology in stages, and provides decision-makers with priority recommendations for technology implementation. In particular, the data of the investment recovery period can help select the most cost-effective technology combination.

Table 2.3 – Effectiveness of ESTs recommended for implementation

Stage	NP3	EST	Efficiency parameters of EST							$F_{in(cal)}$, ths. EUR	T_{pp}, years
			ΔQ, MWh	ΔQ_s,	ΔV_{fuel},	ΔM_{CO2},	ΔM_{Nox}, kg	ΔC, ths.	ΔP, %		
A	1_A										
	2_A										
	… N_A										
	Total A stage										
B	1_B										
	2_B										
	… N_B										
	Total B stage										
C	1_C										
	2_C										
	… N_C										
	Total C stage										
A,B,C	**Total A,B,C stage**										

Table 2.4 presents the results of comparing the 9 studied RIEST strategies and the 0th strategy (leaving the research object in its current state) according to the following effectiveness criteria: relative reduction in the actual amount of investment required for the implementation of EST – $F_{in(act)}$ (in %), increase in the payback period of the studied strategy compared to strategy 1 – ΔT_{pp} (years), specific cost of the obtained ecological and economic effects.

Table 2.4 – Results of comparison of RIEST strategies

RIEST Strategy	Delay periods for the start of stage,			Financial flows to implement strategies, ths. EUR					Criteria for the effectiveness of RIEST strategies						
	ΔT_A	ΔT_B	ΔT_C	F_{lost}	F_{save}	ΔF	$F_{in(cal)}$	$F_{in(act)}$	$\delta F_{in(act)}$, %	ΔT_{pp}, years	*Δq*, EUR/MWh	Δv_{fuel}, EUR/th.m³	*Δc*, EUR/EUR	Δm_{NOx}, EUR/kg	*Δp*, EUR/%
0	∞														
1			0												
2	0	0	1												
3			2												
4			0												
5	0	1	1												
6			2												
7			0												
8	0	2	1												
9			2												

According to the data presented in Table 2.4, the most effective RIEST strategy, which requires the least amount of investment, is determined, and a reasoned technical decision is made regarding the feasibility of its practical implementation.

Overall, this information map is an efficient tool that can help you choose the best energy-saving strategy with the least amount of resources, and has high theoretical and practical value.

Conclusions to the Chapter 2

1. The conceptual foundations of improving the energy and environmental security of municipal energy have been analyzed and systematized, which include: the main provisions of the theory of sustainable development, the principles of the recycling economy, the concept of energy modernization of urban heating networks, the justification of the feasibility of rational implementation of energy-saving and environmental protection measures in the field of heat supply, and an improved methodology for the rational implementation of energy-saving technologies in the municipal sector has been proposed.

2. The method of rational implementation of energy-saving technologies in the field of heat supply has been improved by introducing new ecological and economic criteria for assessing the effectiveness of energy modernization procedures for technical systems "producer-consumer of thermal energy", the introduction of which allows for a more complete assessment of the degree of rationality of the use of

investment resources when carrying out energy-efficient measures and implementing programs to improve the energy and environmental security of urbanized areas.

3. The feasibility of using and developing an information map form for multi-criteria assessment of the effectiveness of various strategies for the rational implementation of environmental energy-saving technologies based on the criteria of the specific cost of achieved environmental, economic and generalized effects has been scientifically substantiated, which constitutes an information basis for making reasoned technical decisions regarding the choice of the most cost-effective procedures for realizing the energy-saving potential of buildings and heat supply systems.

4. A mathematical model for determining parameters and assessing the effectiveness of procedures for the rational implementation of energy-saving technologies has been further developed, which allows taking into account the losses of the integral energy-saving potential of facilities that produce and consume thermal energy in the initial and final periods of their phased energy modernization; this allows increasing the accuracy and reliability of determining the predicted environmental and economic effects.

CHAPTER 3 INTERNATIONAL EXPERIENCE OF STATE REGULATION IN THE FIELD OF HEAT SUPPLY

Based on the theoretical framework of sustainable development, in the context of an increasingly harsh global social environment, international experience can provide a reference for regulatory practice. Energy conservation, emission reduction and environmental protection have become important issues in global green development. As an important sector in the energy sector, the high energy consumption, high pollution and low efficiency of the heating industry have become one of the prominent issues that need to be resolved in the world. To this end, governments have taken measures to regulate the heating industry to reduce energy consumption, reduce pollution and protect the ecological environment.

Government regulation of the heating industry has important purposes and significance. On the one hand, it can protect the environment, reduce energy consumption, improve resource utilization and promote sustainable economic development; on the other hand, government regulation can guide social and market behavior, standardize industry development, improve the level of industry development and promote the sustainable development of the country and the industry. By summarizing the reform and development of regulations in the heating industry in some European and Asian countries, and comparing the regulatory experience of different countries, in the last section of this chapter, we selected a building in Vinnytsia, Ukraine as a typical case for analysis to verify the actual effect of energy-saving technology.

3.1 Regulation and development of municipal energy in European countries

The development of the heating industry in European countries is influenced by many factors, including energy policies, environmental regulations, market-oriented reforms, and the intensity of government supervision. The EU's goal is to achieve climate neutrality by 2050 and strive to achieve a net zero greenhouse gas emission economy. Decarbonization of the EU heating and cooling industry is crucial to achieving this goal. The heating and cooling industry lags behind the power generation industry in reducing carbon emissions and adopting renewable energy. They account for 42% of the EU's final energy consumption, of which 75% comes from fossil fuels. Germany faces even greater challenges, with heating and cooling accounting for 52% of energy use, of which 85% relies on fossil fuels [91]. This section takes Denmark, Germany and Ukraine as examples to analyze their regulatory reform paths, implementation results and challenges in the heating industry, and extracts policy implications through comparative studies.

Reform and development of heating regulations in Denmark. Denmark's heating industry reform is regarded as a model for global energy transformation. Its success is not only due to clear climate goals, but also relies on a systematic policy framework and a multi-party interest coordination mechanism. As one of the first countries to propose the goal of "carbon neutrality", Denmark began to explore the path of energy independence after the oil crisis in the 1970s. At that time, 90% of the country's energy relied on imported fossil fuels, and the heating system was mainly based on decentralized oil boilers. Energy security and environmental pollution issues became increasingly prominent [92]. Against this background, the Danish government promulgated the first "Heating Act" in 1979, which forced local governments to formulate regional heating plans and give priority to the use of industrial waste heat and local biomass resources [93]. This policy marked Denmark's transformation from "passively responding to energy crises" to "actively building a sustainable energy system".

Innovation in policy tools is a core feature of Denmark's reform. The revised "Heating Planning Act" in 2005 further strengthened legislative constraints, requiring all cities to submit detailed heating technology roadmaps within a ten-year cycle and prohibiting the construction of new coal-fired boilers. For example, in its 2013 plan, the Copenhagen City Government clearly required the elimination of all fossil energy heating facilities by 2030, and the construction of a zero-carbon heating network based on North Sea wind power and biomass energy. To achieve this goal, Denmark designed a two-track incentive mechanism of "carbon tax + subsidy": in 2023, the carbon tax rate for the heating industry will reach 110 euros/ton of CO_2, 30% of the tax will be used specifically for the transformation of regional heating pipelines, and the rest will be invested in heat pump and hydrogen energy technology research and development. In Aarhus, the local government attracted more than 200 million euros in private investment through the "Biomass Boiler Subsidy Program", which increased the city's biomass heating share from 15% in 2010 to 45% in 2023 [94].

Mandatory requirements of technical standards have also driven industry transformation. Since 2018, the Building Energy Efficiency Ordinance has stipulated that new buildings must be connected to the district heating system, and the energy consumption per unit area must not exceed 50 kWh/m^2/year. This policy has spawned a wave of technological innovation: the Amager community in Copenhagen has reduced heating energy consumption to 40% of traditional systems through ground source heat pumps and seawater waste heat recovery technology [95]. In addition, the introduction of digital supervision tools has significantly improved system efficiency. In 2021, the Danish Energy Agency requires all heating companies to install smart metering devices to monitor user demand in real time and dynamically adjust the amount of heat supplied. Data shows that this measure has reduced the national heating network loss rate from 12% in 2015 to 6% in 2023 [96].

According to the study in reference [93], the heat savings for all existing buildings in Denmark (compared to 2020) will be an average of 12% in 2030 and 30% in 2045. The energy consumption savings and efficiency of industry will increase by 12% in 2030 and 32% in 2045. The heating system will gradually transition to the fourth generation of district heating (half in 2030 and all in 2045), which can reduce the grid losses of the district heating system, improve the efficiency of energy conversion devices, and increase the utilization of waste heat from industrial processes. Figure 3.1 shows the heating demand and production implemented in the Danish system in 2020, 2030 and 2045.

This chart shows that Denmark has achieved comprehensive decarbonization of its heating system by gradually phasing out fossil fuel boilers through improving building energy efficiency (heat demand in 2045 will be 30% lower than in 2020), expanding district heating (covering 63% of heating demand), and integrating industrial waste heat, geothermal energy, and renewable energy (such as heat pumps and solar thermal).

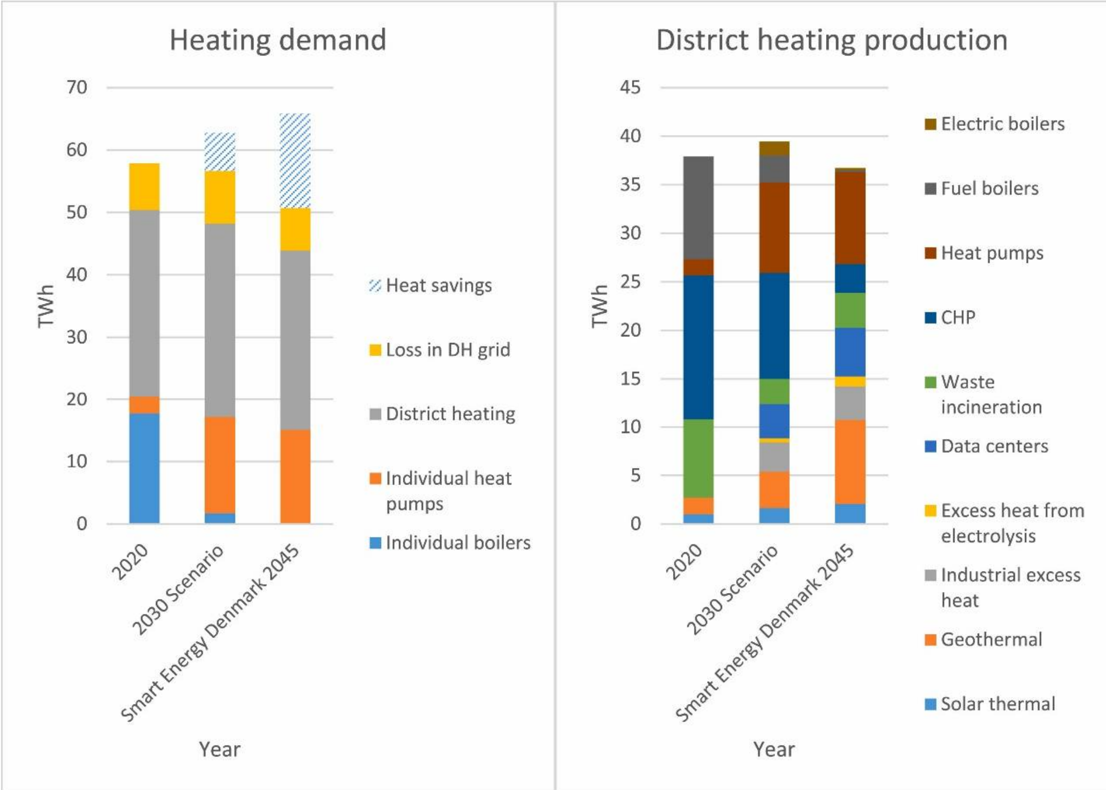

Fig. 3.1 – Heating demand and production in Denmark in 2020, 2030 and 2045

This transformation relies on cross-departmental coordination of smart energy systems and waste electricity heating technology, which verifies the feasibility of Denmark replacing traditional energy with low-carbon heat sources, provides key support for its 2045 carbon neutrality goal, and provides a replicable technical path for similar climate actions around the world.

However, the Danish model also exposes the limitations of institutional design. First, the dependence on central government subsidies has become a burden for small and medium-sized cities. For example, Sonderborg, a city with a population of less than 50,000, 80% of the funds for its district heating project come from the national "Green Transformation Fund", but the fund allocation tends to be large cities, resulting in lagging technology upgrades in small towns [97]. Second, the excessive promotion of biomass energy has caused controversy. Although Denmark claims that its biomass raw materials come from sustainable forestry, the international environmental organization Friends of the Earth pointed out that some of the wood imported comes from illegal logging areas in the Baltic Sea, which may exacerbate ecological damage [98]. More seriously, the high carbon tax policy has pushed up the cost of industrial heat, forcing three paper companies to relocate their production lines to Poland, resulting in the loss of local jobs.

Despite this, Denmark’s experience still provides important inspiration for other countries. The key to its success lies in the construction of a policy system that integrates “legislative constraints, market incentives, and technical standards” and resolves social resistance through a public participation mechanism. For example, during the formulation of Copenhagen’s heating plan, the city government organized more than 200 community hearings to incorporate residents’ concerns about heating prices into technical route adjustments. This “consensus-driven” reform path has enabled Denmark to achieve deep decarbonization of the heating industry while maintaining economic growth. As the International Energy Agency commented: “Denmark has proven that a high welfare society and radical climate policies can coexist—as long as the institutional design takes into account both efficiency and fairness” [99].

Reform and development of heating regulations in Germany. Germany's heating is divided into centralized heating and independent heating. Germany's centralized heating system was developed after World War II. Influenced by the different political systems at the time, West Germany's thermal power plants put efficiency improvement first, and centralized heating accounted for 9% of the heating system. High-rise residential buildings with relatively high population density basically adopted centralized heating; East Germany inherited the development ideas of the former Soviet Union, vigorously developed centralized heating, and put reducing investment first, and centralized heating accounted for 30% of the heating system. Today, centralized heating in Germany only accounts for about 12% of the total heating system. Although it accounts for a small proportion, it is very developed. The heat source of centralized heating is the thermal power plant and peak-shaving boiler of the regional energy network, and independent heating boiler. Among them, cogeneration accounts for 60% of the centralized heating system, and the heat obtained by absorbing solar energy is used as a heat supplement for peak-shaving boilers and independent heating boilers. Germany is the country with the largest installed capacity of cogeneration in Europe. Before the outbreak of the world's first oil crisis, Germany's cogeneration used coal. After the crisis, Germany began to explore natural gas and biomass energy as sources of cogeneration. At present, Germany mainly uses natural gas and fuel oil, with a small amount of electricity, coal and renewable energy for cogeneration.

Thermal power production companies often pay great attention to production efficiency. The first is to control the size of the boiler. Modern boilers can accurately control the mixing ratio of fuel and air to ensure full combustion of the fuel and reduce harmful gases produced by incomplete combustion; secondly, the control system must be improved, and energy efficiency must be improved through reasonable flue design, recovery preheating and other measures.

Germany's heating industry reform is centered on "renewable energy integration" and "market-based mechanisms", demonstrating the complex balance of industrialized countries in energy transition. Since the release of the "Energy Transition Strategy" in 2011, the German government has clearly stated the goal of renewable energy accounting for 30% of the heating sector by 2030 [100]. The realization of this goal depends on the dual drive of legislative innovation and technology promotion, but it also faces resistance from traditional energy interest groups and challenges of social equity.

Germany's "Renewable Energy Heating Law" stipulates that new buildings must meet at least 65% of their heating needs from renewable energy, and existing buildings are promoted through subsidy policies [101]. For example, the "Heat Pump Promotion Plan" implemented by Bavaria provides households with a maximum of 40% installation subsidies, which has increased the state's heat pump coverage rate from 5% in 2015 to 18% in 2022. In addition, Germany has established a special fund through the Renewable Energy Law to support the upgrading of regional heating pipelines. In the "Geothermal Heating Network Expansion Project" launched by the city of Berlin in 2021, the public-private partnership (PPP) model attracted 280 million euros in private investment, covering an additional 80,000 households).

Germany's heating industry seeks a balance between marketization and government regulation. In recent years, market competition has gradually increased, with increased participation from enterprises. Among them, the heat pump market has developed rapidly, and heat pump technology, as an efficient and environmentally friendly heating method, has been widely promoted in Germany in recent years. Affected by energy policies and market demand, consumer demand for heat pumps has increased significantly, with the number of newly installed heat pumps reaching 230,000 in 2023 and expected to increase to 350,000 in 2024. This trend reflects consumers' increased demand for renewable energy heating systems and expectations for future policy changes.

The application of district heating systems in Germany is also expanding. According to a study of European district heating, consumers' perceptions and attitudes towards district heating are influenced by a variety of factors, including socio-demographic factors, attitudes and regulations. The German government supports the sustainable development of the heat pump industry through fiscal deficits and low-interest loans. For example, current poverty policies cover 70% of installation costs, making the installation of heat pumps attractive to homeowners under political uncertainty.

Today, Germany's centralized heating system is still well developed, but the proportion of independent household heating is increasing year by year. In Germany, one or several households use one boiler for heating. Many buildings in the city have natural gas boilers in their basements, which are responsible for heating and hot water supply for the entire building. Most households in Germany use natural gas, fuel oil and other methods for heating, and a small number of residential buildings use electricity or coal for heating. In recent years, renewable energy sources such as solar energy and wind energy have gradually been applied to independent heating, and the proportion of fossil energy in building heat sources is decreasing.

The experience of regulatory reform in Germany's heating industry shows that through strict legal standards, reasonable market mechanisms, advanced technology applications and effective fiscal incentives, the heating industry can be driven towards low carbonization and high efficiency. Germany's experience has important fruitful significance for the sustainable development of other countries in the heating industry. In contrast, Denmark's approach of forcing the elimination of fossil energy through legislation is more radical, but Germany's gradual path is more suitable for large economies with complex industrial structures.

Reform and development of heating regulations in Ukraine. Ukraine's heating sector reform has undergone a complex process of transition from the Soviet planned economy model to a market economy. Ukraine's heating system has long relied on centralized heating, with old infrastructure, low energy efficiency, and high dependence on imported natural gas from Russia. Since the Crimean crisis in 2014, the Ukrainian government has accelerated the pace of energy independence and heating sector reform, promoting the transformation of the heating industry to a low-carbon one through legislation, market incentives and technological innovation.

The Ukrainian government's reforms have "energy independence" and "heating modernization" as their core goals. In 2017, Ukraine promulgated the "Energy Efficiency Law", which established a goal of improving the energy efficiency of the heating industry by 30% by 2035. In 2020, Ukraine issued the "Heating Modernization Strategy", proposing to gradually phase out inefficient gas boilers, promote renewable energy heating, and focus on the development of biomass energy and heat pump technology.

Due to unfortunate geopolitical events, Ukraine's thermal power generation plays a vital role in balancing and maneuvering the energy system, but it has also been severely affected by hostile attacks. Despite Ukraine’s predominant use of coal and natural gas and the “green coal paradox” phenomenon, the importance of thermal power generation cannot be underestimated. Thermal power generation has suffered severe damage, and Ukraine has had to rebuild it using advanced technologies and make extensive use of renewable energy. This will bring several significant advantages, including decentralizing the energy system, making it more flexible and less vulnerable to hostile attacks. In addition, renewable energy will help avoid dependence on imported energy carriers. Heat pumps are one of the most promising energy technologies for heating [102].

In 2018, 4.6 MW of heat pumps were installed in Ukraine [103]. Ground, air, water and/or sewage collectors can serve as heat sources. In 2020, heat pumps generated 52 ktoe of energy in Ukraine (36 ktoe of air heat, 10 ktoe of geothermal heat, 6 ktoe of water heat). In contrast, we can say that due to the martial law, the exact data on new or existing installed capacity in the heating sector is unknown, but it is known that more than 500 MW of new solar photovoltaic power generation was installed in just 8 months in 2024. Ukraine has a ground heat potential of 6293 ktoe/year and an air heat potential of 6307 ktoe/year [103]. The heat transfer medium temperature of large systems in Ukrainian buildings is 70–150 °C, and the heat transfer medium temperature of small systems is 70–95 °C. Heat pumps provide heat at temperatures of 35–65 °C and use up to 80% renewable energy, with the remaining 20% of electricity used to heat water and houses [103], which is only possible in new or heavily modernized buildings. Another basic prerequisite for the operation of heat pumps is a stable and reliable electricity supply. In Ukraine, several heat pump manufacturers have joined together to form the Ukrainian National Heat Pump Association. Foreign-made pumps such as Mitsubishi Electric, Daikin, Viessmann, Buderus, etc. dominate the domestic market. Investment in heat pumps is relatively high: heating 100–300 square meters requires 10,000 to 15,000 euros [104] (or an average of 285–715 US dollars per kilowatt, depending on the technology [103]). Drilling works are also expensive. From 2024, the scheme will apply to apartment buildings, social infrastructure (schools, kindergartens and hospitals) and social facilities (shopping centers, etc.), but they can also be used for individual households in urban or rural areas. In Ukraine, 79.2% of the population lives in cities [105], but not all urban areas have district heating. Therefore, district heating can be used in both urban and rural areas.

Ukraine's heating industry reform has taken mandatory measures in terms of technical standards and energy efficiency improvement. The revised "Building Energy Conservation Regulations" in 2019 require that the heating systems of new buildings must meet minimum energy efficiency standards (energy consumption per unit area shall not exceed 80 kWh/m^2/year) and mandatory promotion of smart heat metering systems. However, Ukraine's heating industry reform still faces many challenges. First, the reform of Ukraine's energy subsidy policy has caused social controversy. In 2022, the Ukrainian government cancelled gas subsidies, resulting in a 30% increase in residents' heating costs, triggering large-scale protests. Second, the promotion of biomass energy is affected by the uncertainty of resource supply. Although Ukraine has abundant agricultural waste resources, its biomass fuel market is not yet mature, and some areas face fuel shortages. In addition, due to the unstable investment environment, foreign investment in Ukraine's heating industry is still cautious.

Nevertheless, Ukraine's experience shows that even under economic and geopolitical challenges, the government can still promote the modernization and transformation of the heating industry through policy incentives, market reforms and technological innovation. The core of the Ukrainian model lies in the trinity strategy of "energy security-market reform-technological innovation", which gradually reduces dependence on fossil fuels, improves heating efficiency, and strengthens the construction of regional heating systems. These experiences are of great reference significance for other developing countries facing energy security challenges.

3.2 Regulation and development of municipal energy in Asian countries

Reform and development of heating regulations in China. China's central heating system is mainly coal-fired, with about 72% of China's central heating coal-fired heat sources, of which coal-fired cogeneration accounts for 45% and coal-fired heating boilers account for 27%. In terms of the operation of China's heating system, China's traditional central heating system is a push-type system that pushes a large amount of heat to high-rise or multi-story buildings after exchanging heat from the heat source through a large heat exchange station. The heat supply is usually determined according to the change in outdoor temperature. Due to the lack of control devices, heat users have limited or no control over indoor heat supply. Therefore, building heating systems generally operate at a fixed flow rate, and the room temperature reaches the standard of 18-20°C. In addition, most central heating systems only provide indoor heating, not domestic hot water.

Since the 1990s, the Chinese government has successfully introduced municipal regulations on urban gas, road lighting, drainage and water supply. However, national regulatory laws in the field of heating still need to be included. Existing provincial heating management regulations need to be supported by laws to regulate the heating market, respond to changes in policies and standards under the new situation, and provide policy basis for clean, efficient and safe modern heating systems.

China's heating plan is part of the city's master plan and is formulated based on the local population and building area growth in the next five, ten or fifteen years. The heating plan usually has a relatively fixed format and content, such as explaining relevant national and local policies and regulations; highlighting the key points of the city's master plan; predicting heat load, and planning heat sources and heat networks during the planning period.

The reform of China's heating industry takes the "dual carbon goals" and "clean heating" as the strategic core. Through the combination of top-level design, technological innovation and market incentives, it has built the world's largest low-carbon heating system. Since the implementation of the "Air Pollution Prevention and Control Action Plan" in 2013, more than 500,000 decentralized coal-fired boilers have been eliminated in northern China, reducing the burning of decentralized coal by 140 million tons, and promoting the annual average concentration of PM2.5 in the Beijing-Tianjin-Hebei region from 93 micrograms per cubic meter in 2015 to 40 micrograms per cubic meter in 2023, a decrease of 57% [106]. This achievement is due to the strong support of the central government. For example, the “coal to electricity” policy has invested more than 100 billion yuan, covering 15 provinces (autonomous regions and municipalities) in the north, with a maximum subsidy of 24,000 yuan per household, and a tiered electricity price discount (peak-valley price difference of 0.3 yuan/kWh), which directly promoted the installed capacity of air source heat pumps from less than 10% in 2015 to 45% in 2023, covering a population of 120 million [107]. As a demonstration city, Beijing has completely eliminated coal-fired heating through the “coal-free” project. By 2023, the proportion of coal-fired heating will drop to 0.5%, reducing annual carbon dioxide emissions by 12 million tons, equivalent to the carbon sequestration capacity of planting about 70 million trees [108].

The General Code for Energy Conservation and Renewable Energy Utilization in Buildings (GB 55015-2022), released in 2022, stipulates that the heating energy consumption per unit area of new buildings shall not exceed 65 kWh/m²/year, and that household metering and intelligent temperature control systems shall be installed. Data show that after the implementation of the new code, the heating energy consumption of new buildings in the north has been reduced by more than 30%, saving about 18 million tons of standard coal annually [109]. Xiongan New Area has built the world's largest medium-deep geothermal heating network through the "geothermal +" multi-energy complementary model, covering an area of 50 million square meters, replacing 3.2 million tons of coal annually, and reducing carbon dioxide emissions by 2.2 million tons, as shown in Table 3.1. Its technical path includes heat extraction from a 1,500-meter deep well, cascade heat exchange and cross-seasonal heat storage, and its thermal efficiency is 40% higher than that of traditional systems [110]. The large-scale development of geothermal energy has become the mainstay of China's clean heating. In 2023, the country's direct geothermal utilization will reach 1.4 billion square meters, accounting for 40% of the global total. Hebei Province has built a "geothermal heating demonstration province" based on the resources of the North China Plain, saving 8 million tons of standard coal annually [111].

Table 3.1 – Emission reduction effect of Xiongan New Area geothermal heating network

Index	Numerical value
Coverage area	50 million square meters
Replacement of coal	200,000 tons/year
Replacement of coal	2.2 million tons/year
Average depth of geothermal wells	1500m

In terms of geothermal resource reserves, China is rich in geothermal resources, with a calorific value of 3.06×10^{18}kWh/year, accounting for about 8% of the world's geothermal energy reserves. Table 3.2 evaluates China's three geothermal resources [112], describing the temperature level, depth, and reserve size.

Table 3.2 – Three geothermal resources and technical parameters in China

Geothermal resources	Temperature levels and depth	Resource scale
Shallow geothermal	Within 200 m below the surface, the temperature is below 25°C.	Annual recoverable resources equivalent to 700 million tons of standard coal.
Hydrothermal geothermal	Thermal resources contained in groundwater or steam buried thousands of meters deep: (a) high-temperature geothermal resources (above 150°C); (b) medium-temperature geothermal resources (90-150°C); (c) low-temperature geothermal resources (below 90°C).	The reserves are equivalent to 1.06 trillion tons of standard coal.
Hot dry rock	The temperature of high-temperature rock masses buried more than 1 km below the surface is usually higher than 200°C, and there is no fluid or a small amount of underground fluid inside.	The reserves of hot dry rock geothermal resources are equivalent to 85.6 trillion tons of standard coal.

The reform of China's heating industry began with the urgent need to adjust the energy structure and transform to a low-carbon economy. The traditional coal-based centralized heating model has long dominated the northern region, but the air pollution caused by coal combustion has become increasingly prominent. In 2017, the National Development and Reform Commission and ten other ministries jointly issued the "Northern Region Winter Clean Heating Plan", which clearly listed the "2+26" cities as key transformation areas, and promoted the transformation of energy consumption structure through "coal to gas", "coal to electricity" and the use of renewable energy. By 2021, the clean heating area in the northern region will reach 15.6 billion square meters, replacing more than 140 million tons of scattered coal. The PM2.5 concentration in Beijing-Tianjin-Hebei and surrounding areas has dropped by about 60% compared with 2013, showing significant results in environmental governance [113]. Table 3.3 lists the key indicators of clean heating in northern China from 2015 to 2023.

Table 3.3 – Main indicators of clean heating in northern China
(according to the National Energy Administration of China)

Index	2015	2023	Increase/decrease
Clean heating coverage rate (%)	28%	72%	157%
PM2.5 concentration (μg/m³)	93	40	-57%
Geothermal heating area (billion m^2)	3.8	14	268%
Air source heat pump installed capacity (10,000 units)	120	800	567%

Technological innovation is reshaping the heating industry. Waste heat recovery technology converts industrial waste heat into urban heat sources. Jinan City has covered more than 20 million square meters of buildings through waste heat heating from steel enterprises. Ground source heat pump systems are rapidly popularized in urban agglomerations in the Yangtze River Basin, using shallow geothermal energy to achieve efficient heating with an energy efficiency ratio of more than 4.0. Breakthroughs in cross-seasonal heat storage technology have significantly improved the stability of solar heating. The world's first photovoltaic + cross-seasonal heat storage heating project built in Gonghe County, Qinghai, has a heat storage efficiency of more than 75%. These technological breakthroughs have promoted the transformation of heating systems from a single heat source to a multi-energy complementary smart energy system.

Future development trends show multi-dimensional evolution. In terms of technical paths, cutting-edge fields such as nuclear energy heating and hydrogen energy heating are accelerating their layout. Shandong Haiyang Nuclear Power Station has achieved commercial operation of 4.5 million square meters of nuclear energy heating. In terms of system architecture, it is upgrading from a single heating network to a "heat, electricity, hydrogen" multi-energy fusion system. The multi-energy complementary integrated pipeline corridor planned and constructed in Xiongan New Area is a typical example. In terms of service model, heating companies are accelerating their transformation into comprehensive energy service providers, providing value-added services such as energy-saving transformation and smart operation and maintenance. The profound changes in the industry ecology are reshaping the warm picture of winter heating in urban and rural areas in China.

Reform and development of heating regulations in South Korea. The development time of the heating industry in South Korea is the same as that of China. It has developed rapidly in just a few decades, which is inseparable from their scientific regulation. Korean law stipulates that heating energy consumption must be measured by hot water flow meters. South Korea initially adopted household heat meters, and later issued laws allowing the use of hot water meters for household metering. In South Korea, about 600,000 users are heated and supplied with domestic hot water by the district heating system throughout the year. The district heating company is responsible for the installation of heat exchange stations and heat meters, and is responsible for sending heating and domestic hot water fees to housing companies every month. The housing company is responsible for the operation, maintenance and collection of monthly heating fees from users of heat exchange stations. Each heat bill includes a fixed part and a variable part. If household-by-household, the variable part is equal to the heat supplier's heat price multiplied by the heat meter reading plus 10%. This 10% is to take into account the pipe network loss between the heat exchange station and each consumption point.

South Korea's heating industry regulatory reform is centered on "market-oriented" and "green transformation". Through policy incentives, technological innovation and market mechanism adjustments, it gradually promotes the transformation of traditional high-carbon heating systems to low-carbon and high-efficiency directions. As a country with scarce energy resources, South Korea's heating industry is highly dependent on imported fossil fuels. In order to meet the challenges of energy security and climate change, the South Korean government has accelerated the reform of the heating industry since 2010, focusing on improving energy efficiency, promoting renewable energy and building a market-based competition mechanism.

The policy basis for the reform of South Korea's heating industry is the Basic Law on Low-Carbon Green Growth (2010) and the Heating Business Act (revised in 2015). Among them, the Heating Business Act clearly requires heating companies to increase the proportion of renewable energy heating to 30% by 2030, and to force new buildings to connect to the district heating system.

South Korea has its own unique way of measuring heat energy. South Korea is the only country that has laws requiring the use of hot water flow meters to measure heating energy consumption. At first, South Korea stipulated that buildings with centralized heating must use household metering, and later switched to hot water meters for household metering. The main reason for this change was that the performance of the heat meters developed at that time was poor, and the poor quality of hot water caused the flow metering components to wear out faster, so the heat meters had to be frequently inspected. In addition, the expected life of the batteries in the heat meters is only five years. Currently, South Korea's main heating method is low-temperature hot water floor radiant heating. The circulating water flow is large and the temperature difference is small. This greatly improves the accuracy of the hot water meter's calculation of heat consumption, and the cost of this type of hot water meter is also low.

Reform and development of heating regulations in Japan. The development of the centralized heating system in Japan is relatively fast, and the development in different regions is different. The heating industry in Japan adopts a fixed quota system and a two-step charging system. The reform of heating in Japan is mainly focused on the reform of the charging system. For users with different heating properties, almost all adopt a two-step charging system. For some customers with little difference in heating volume, a single fixed quota charging system is adopted. The heating fee is determined by the following fees, that is, based on appropriate heat supply and demand planning, the balance after deducting the amount to be deducted from the total amount of calculated manufacturing expenses, sales expenses, general administrative expenses and non-operating expenses, plus a reasonable profit amount.

Many customers are the most basic force in determining the charging system in Japan. Whether a charging system that residents believe is fair and reasonable can be formulated is the main purpose of the Japanese government's price control of the heating industry. At present, there are two types of charging adopted by the heating industry in Japan: a fixed quota system and a two-part charging system (fixed fee plus actual heat metering fee). The characteristics of the fixed-rate heating fee calculation system are: it is mainly applicable to some users with little difference in heating volume, eliminating the cost of calculating the complex heating volume and heating fee separately, and only needs to adopt a single fixed-rate charging system for the cheapest price, while almost all heating in the region adopts a two-part charging system. The main feature of the two-part charging system is that a fixed part is used as the basic fee for heating fees, and the variable part is charged according to the actual amount of heat used by the household. The basic price of heating is based on the appropriate heat supply and demand market, the normal operation of heating enterprises, and the consumption level of consumers.

Overall, Japan's heating situation has the following characteristics:

First, the development of centralized heating systems is relatively fast, especially in the Kanto region centered on Tokyo. At present, the centralized heating area accounts for 60% of the country.

Second, Japan's centralized heating systems are mostly small-scale and are mostly used in business facilities such as office buildings, and the proportion used for residential buildings is very small.

Third, Japan's heating system pays great attention to energy saving and environmental protection. Japan is one of the industrialized developed countries with the most scarce energy resources in the world, but at the same time, its comprehensive energy utilization efficiency is also one of the highest in the world. The Japanese government has spared no expense in developing a number of energy-saving and environmentally friendly technologies, such as the use of thermal power supply systems, heat storage tanks, and the use of urban waste heat as energy, in order to improve energy utilization efficiency.

3.3 Comparative analysis of the experience of different countries in regulating urban heat supply systems

In order to more clearly demonstrate the experience of different countries in regulating the heating industry, this study compares and analyzes the regulatory models of Denmark, Germany, Ukraine, China, South Korea and Japan, and summarizes their core characteristics (Table 3.4).

Table 3.4 – Comparison of heating industry regulatory models in different countries

Country	Regulatory Model	Heat Billing Method	Government Support Policies	Market Competition Mechanism	Energy Efficiency & Environmental Requirements
Denmark	Legislative constraints + market incentives + technical standards	Household smart metering + dynamic pricing	Combination of carbon tax and subsidies (e.g. 30% of carbon tax used for pipeline network transformation) and green transformation fund support	District heating is dominated by monopoly, with private participation	Mandatory phase-out of fossil fuel heating, building energy efficiency standards (50 kWh/m² / year), renewable energy share targets
Germany	Enforce heat metering and set strict regulations	Two-part charging (fixed fee + on-demand billing)	Establish energy conservation law, government subsidies for energy conservation renovation	Partial competition in the heating market to encourage private enterprises to participate	High standard building insulation requirements to improve heating efficiency
Ukraine	Market-oriented reform of the heating industry to promote energy independence	Gradually shift from unified pricing to market-based pricing	Promote the use of renewable energy and implement energy-saving policies	Heat market reform to encourage private investment	Improve heating efficiency, reduce energy waste, and promote modern energy-saving technologies
China	Gradually promote market-oriented reforms and strengthen environmental protection supervision	The fee is mainly charged by area, and heat metering is promoted in some areas	Heating subsidy policy to encourage energy-saving building renovation	A competitive mechanism is being established, and some regions are introducing private capital	Promote clean heating, develop cogeneration, geothermal and solar heating
South Korea	The law stipulates the method of measuring heating energy consumption	Heat distribution using hot water flow meter	Encourage energy-efficient buildings and technologies and promote smart heating systems	The heating market is commercialized, and enterprises are responsible for collecting heating fees and maintaining equipment	Low-temperature hot water floor radiant heating, good energy saving effect
Japan	The heating industry mainly provides heating for commercial office buildings and adopts strict fee control	Adopting a fixed-rate system and a two-part charging system (basic fee + actual heat consumption)	Focus on supporting energy-saving technologies and guide enterprises to invest in environmental protection equipment	High degree of marketization, multiple models coexist	High-efficiency energy-saving technologies such as combined heat and power, heat storage tanks, and waste heat utilization are widely used

Looking at the practice of government regulation of the heating industry in typical European and Asian countries, we can draw several improvement.

First, improve the heating price system. Heating prices are the most sensitive topic for residents and heating companies. A perfect heating price system is the key to promoting the stable and healthy development of the heating industry. In order to make heat a real commodity, it is necessary to change the phenomenon that heating fees are out of touch with heat. It is necessary to truly realize that you pay how much heat you use. This requires household control of heat and the use of heat meters for household metering. From the perspective of the international heating reform process, the collection method of heat fees basically goes through two stages: one is charging according to the building area, and the other is charging according to the amount of heat used, that is, metered charging. In metered charging, the heat price composition structure is clearly proposed, that is, the heat price components are fixed fees and floating fees. It can be seen that for China, which is currently charging by area, heat metering is the only option. The implementation of heat metering is imperative. The reform practice of the two-part heating fee system will be further deepened, paving the way for the establishment of a sound heating price system.

Second, strengthen technological innovation in the heating industry. Many European countries have done a lot of scientific research in the field of centralized heating, and the strong support of the government has enabled heating technology and products to be exported overseas. For example, Finland's Evo Group is a multinational group engaged in environmental protection and energy conservation research. Its main task is to provide detailed consulting services for the generation and transportation of electricity, operation and maintenance, project development and investment, in order to improve its brand image. While developing technology, developed countries attach importance to the product quality of heating equipment to ensure the reliability of the heating system. Most of their heating equipment manufacturers have obtained ISO quality system certification and have very good experimental equipment, so that products can be continuously updated and transformed. In the process of product production, comprehensive quality management is carried out on each process to ensure that the qualified rate of products leaving the factory is 100%.

Third, appropriately introduce a competition mechanism. Introducing a competition mechanism in the region is a good way for countries to reform the heating industry under the market economy system. For a long time, the heating industry has been monopolized by the central or local governments. Due to the lack of competition, enterprises have relaxed internal management and technological innovation, resulting in low production efficiency and low allocation efficiency. The government should focus on the heating industry and establish a management mechanism that simulates the competition mechanism, so that the heating source is competitively operated by multiple enterprises, give full play to the role of the competition mechanism, and generally put the entire heating industry in an effective competitive state where economies of scale and competitive vitality are compatible.

Fourth, social regulation is particularly necessary. In order to achieve energy saving in heating and build a conservation-oriented society, the role played by the government is crucial. The first thing to do is to raise the energy-saving awareness of the whole society and work hard to build a conservation-oriented society. The government can make extensive use of television, the Internet, newspapers and other media to strengthen the publicity of energy saving, and carry out energy-saving activities in enterprises, institutions, communities and other places to raise residents' energy-saving awareness and turn resource saving into everyone's conscious action. In order to improve the energy utilization rate of heating, the government should publicize the superiority of centralized heating in energy saving and environmental protection, and implement corresponding policy subsidies for centralized heating users, reflecting the economic superiority of centralized heating, so that more users can choose centralized heating. Centralized heating is one of the important signs of modern urban construction, and its main goal is to make full use of energy, save energy and protect the environment. In order to effectively solve the problem of China's energy reserve shortage, all regions should actively develop and utilize a variety of renewable resources and clean energy, and gradually explore the use of nuclear energy, geothermal energy, garbage, solar energy, biogas, biogas and other energy sources as heating sources. While making full use of existing resources, European countries have also made a lot of efforts in the utilization of waste resources such as garbage and sawdust, providing China with very valuable experience in the development and utilization of waste resources. In view of China's current economic situation and technical conditions, garbage is a feasible heating energy with good social and environmental benefits. Recycling various industrial and domestic garbage, and generating heat energy for production and life use, not only saves energy shortage problems, but also is conducive to environmental protection, and can also obtain good economic benefits. Therefore, the national energy department should adopt corresponding policies.

3.4 Proposals for increasing the efficiency of state regulation of heat supply

From the above comparative analysis, it can be seen that different countries have adopted different strategies in regulating the heating industry, but generally they show several common trends.

First, promote heat metering and charging. Most countries have adopted a model of charging according to heat consumption to promote energy conservation and reduce energy waste.

Second, strengthen government policy support. Countries such as Germany, France, and South Korea have energy-saving subsidies or building insulation standards to improve energy efficiency.

Third, introduce market competition. Although countries such as Russia are still dominated by state-owned enterprises, most developed countries have opened up the market and introduced competition mechanisms to improve the quality of heating services.

Fourth, improve environmental protection requirements. Including the use of clean energy, cogeneration, waste heat recovery and other methods to improve the sustainability of the heating industry.

With climate change and increased energy consumption, the supervision of the heating industry has received more and more attention. As a regulatory department, the government bears the important responsibility of maintaining the stability and healthy development of the heating industry. However, due to various reasons, there are still some shortcomings in the efficiency of government supervision of the heating industry. The following are suggestions to improve the efficiency of government supervision of the heating industry.

First, establish a sound supervision system. The government should formulate more stringent laws and regulations, establish a sound supervision system and mechanism, including policy measures, regulatory agencies, and regulatory processes. Especially in the quality supervision of heating enterprises and products, the government should provide more human, material and financial support to the regulatory authorities, so that the regulatory authorities can be more precise, strict and effective in quality supervision.

Second, improve the quality of regulatory personnel. The professional quality and regulatory ability of regulatory personnel directly affect the efficiency of supervision. Therefore, the government should increase the training and education of regulatory personnel, improve their professional quality, build a high-quality team, and ensure that the supervision work has a wide coverage, strict standards, and strong execution.

Third, strengthen communication and coordination with heating enterprises. The government should strengthen communication and coordination with heating enterprises and related industries, understand the actual situation and needs of enterprises, and provide them with better regulatory services. This will not only fully protect the interests of enterprises, but also standardize the management of the heating industry and achieve common development.

Fourth, establish a public supervision mechanism. The government should establish a public supervision mechanism to allow the public to participate in the supervision work, improve the transparency and fairness of the supervision work, and speed up the supervision efficiency. Public supervision will enable the regulatory authorities to pay more attention to the public interest and help the government discover and solve problems.

The above are some suggestions for improving the efficiency of government supervision of the heating industry. Through these suggestions, the government can improve the efficiency of supervision from multiple aspects and more effectively maintain the healthy and orderly development of the industry [114].

Conclusions to the Chapter 3

1. This chapter reveals the key success factors for the transformation and upgrading of heating systems under different development models through an in-depth comparative study of the regulatory systems of the heating industry in major European and Asian countries. European countries, represented by Denmark and Germany, have established a mature market-oriented regulatory system, which has effectively stimulated the technological innovation of enterprises through the market-oriented formation mechanism of heat prices, the carbon emission trading system and strict energy efficiency standards. In contrast, Asian countries pay more attention to the leading role of the government in the construction of heating infrastructure. China has promoted the construction of large-scale heating pipelines through the "cogeneration" policy, forming the world's largest centralized heating system in the northern region. Japan has established a refined heating service quality standard system, reflecting its high attention to user comfort. These differentiated regulatory practices show that the

optimization path of the heating system must be adapted to the local urbanization stage, resources and institutional environment.

2. The study found that successful regulatory reforms focus on grasping three key balances: first, the balance between market efficiency and public services, which requires both guiding the optimal allocation of resources through price signals and ensuring the accessibility of basic heating services; second, the coordination of technological innovation and institutional innovation. Denmark has incorporated the heating pipeline network into the institutional design of the unified planning of municipal infrastructure, creating conditions for the promotion and application of the fourth-generation district heating technology; finally, the connection between long-term goals and transitional arrangements. Germany has set a clear low-carbon roadmap for heating, while giving different-sized enterprises differentiated deadlines for reaching the target. The study also found that the effectiveness of regulatory policies is highly dependent on capacity building at the execution level. The energy efficiency benchmarking system for heating enterprises established by Sweden monitors the energy consumption indicators of each heating station in real time through a big data platform, providing technical support for precise supervision.

3. These international comparative studies not only enrich our understanding of heating system governance, but more importantly, provide an institutional perspective for the next chapter to explore the application scenarios of specific energy-saving and environmental protection technologies. The actual effect of technical solutions depends largely on the policy environment and market structure in which they are located. For example, the rapid promotion of flue gas treatment technology in Germany is

inseparable from its strict law enforcement of "polluter pays"; the reason why Japan's gas boiler low-nitrogen combustion technology is leading is that its step-by-step emission standards force companies to continue to innovate. Therefore, when deeply analyzing various energy-saving and environmental protection technologies in Chapter 4, it is necessary to fully consider the applicable conditions and improvement space of these technologies under different regulatory environments. Especially under the heating management system with Chinese characteristics, how to combine international advanced technologies with local institutional advantages to develop technical routes that meet strict environmental protection requirements and are economically feasible will become the focus of research. This logical transition from regulatory experience to technical solutions reflects the complete chain of theoretical research guiding engineering practice, and also lays a solid foundation for achieving the leap from "learning from the world" to "independent innovation".

4. These practical experiences provide rich cases for verifying the applicability of the RIEST method. In order to verify the actual effect of energy-saving technology, at the end of this chapter, we selected a typical case in the field of education for analysis. And proposed energy-saving technologies and measures for the effectiveness study of the RIEST method.

CHAPTER 4 ECOLOGICAL AND ENERGY MODERNIZATION OF HEATING SYSTEMS. VERIFICATION OF THE METHOD OF RATIONAL IMPLEMENTATION OF ENERGY-EFFICIENT TECHNOLOGIES

Based on the technical analysis, this chapter verifies the actual effect of energy-saving technology through case studies. In recent years, global climate change is an increasingly serious problem. It not only affects the daily life of each of us, but also poses a profound threat to the global ecosystem and socio-economic structure. Energy consumption and carbon emissions have become the focus of global attention. Against this background, the research on energy-saving and environmental protection technologies in the field of heating has become particularly important. Heating systems play a vital role in urban and rural communities, providing people with a comfortable and warm living environment. However, this process usually requires a lot of energy and may cause environmental problems such as carbon emissions and air pollution under improper management. Therefore, it has become urgent and important to find and implement energy-saving and environmental protection technologies in the field of heating.

The purpose of this chapter is to evaluate the current status and energy-saving potential of the 6th Teaching and Sports Complex of Vinnytsia National Technical University, a typical case in Chapter 3, and to draw conclusions from the evaluation results on the effectiveness of implementing the RIEST strategy.

At the same time, the research and application of energy-saving and environmentally friendly technologies in the field of heating are introduced and discussed. By introducing efficient heating systems and reducing energy consumption, we can reduce dependence on limited resources, reduce greenhouse gas emissions, improve air quality, and reduce energy costs. These measures are essential to achieve sustainable urban development and improve the living environment.

Since 2012, with the pressure of social atmospheric environmental problems and increasingly stringent environmental emission indicators, the pollution control of SO_2 and smoke has put forward the requirements of "ultra-clean emissions" or "near-zero emissions". Therefore, centralized heating must be controlled from the source, requiring heat source production units to meet environmental protection requirements and reach ultra-low emission standards.

China's energy consumption is mainly reflected in building energy consumption, industrial energy consumption and transportation energy consumption. In particular, building energy consumption has shown a rapid development trend with the acceleration of urbanization, the rapid increase in the total number of buildings and the improvement of urban residents' living comfort requirements. Winter heating for residents is the largest factor in building energy consumption. At present, the average coal consumption for urban heating in China is about 25-35 kg/m^2 per heating period, which is much higher than the level of developed countries under the same climatic conditions. Therefore, the use of energy is facing a new revolution, and energy conservation and emission reduction, green environmental protection, and sustainable use of energy have become the focus of attention of all countries.

In the context of the general social concern about low-carbon economy, energy conservation and emission reduction, climate change and economic development in the post-crisis era, centralized heating is particularly important as an important infrastructure in urban development. Central heating replaces local decentralized inefficient small boilers through large-scale cogeneration and regional boiler rooms, improving the thermal efficiency of heat sources. However, if economic benefits are pursued alone while environmental protection is ignored, the heat source plant will become a major source of pollution.

4.1 Environmental technologies for cleaning exhaust gases in heating boilers

Flue gas treatment technology program. The application of energy-saving technology not only reduces energy consumption, but also directly reduces pollutant emissions from heating systems. In order to further achieve environmental protection goals, it is necessary to combine efficient flue gas treatment technology to deeply treat pollutants such as nitrogen oxides (NO_X) and sulfur dioxide (SO_2) emitted.

Heating boilers are an important part of modern industry and life. They provide us with essential energy, but the waste gas and waste residue generated in the process of heat energy production also bring environmental and health problems. With the rapid development of global industrialization and the continuous increase in energy demand, the number of heating boilers is also increasing, which leads to a large amount of flue gas emissions and solid waste. At present, the production of heat sources in centralized heating systems is still mainly based on cogeneration and large hot water boilers. In the production process, harmful substances such as smoke, sulfur dioxide, and nitrogen oxides (NO_X) will inevitably be generated, causing deterioration of air quality and damage to the ecological environment. In order to reduce the adverse effects of heating boiler emissions on the environment, governments and environmental protection agencies have implemented a series of regulations and policies requiring operators of heating boilers to adopt appropriate flue gas treatment technologies to reduce the release of harmful emissions.

With the continuous development and progress in the field of heating, the use of equipment such as coal-fired boilers has also increased, but it has also brought serious environmental pollution problems. Therefore, flue gas treatment technology has become an aspect that cannot be ignored in the field of heating. Flue gas treatment technology mainly treats pollutants such as nitrogen oxides, sulfur dioxide, and smoke emitted by equipment such as coal-fired boilers to achieve the purpose of protecting the environment and reducing pollutant emissions.

Flue gas treatment technology solutions mainly include the following:

(1) Combustion optimization technology. Combustion optimization technology mainly reduces the generation of harmful gases by improving the fuel combustion process. This includes measures such as controlling fuel supply, improving combustion control and improving mixing effect. For example, using advanced burner design, adjusting the ratio of fuel to air, optimizing combustion temperature and time, etc., can effectively reduce the generation of nitrogen oxides (NO_X), while ensuring the quality of heating and reducing environmental pollution.

(2) Flue gas desulfurization technology. Flue gas desulfurization technology is to remove sulfides such as sulfur dioxide (SO_2) from flue gas. It uses absorbents such as limestone or alkaline solutions to react with SO_2 in flue gas to generate sulfates, which are captured and formed into solid waste. Desulfurization technologies usually

include wet desulfurization, dry desulfurization and semi-dry desulfurization methods, among which wet desulfurization technology is the most common one.

(3) Particle capture technology. Particle capture technology is used to remove suspended particulate matter in flue gas, including dust and particulate pollutants. Commonly used technologies include electric bag filters, wet dust collectors, etc. The electric bag filter captures the particles under the action of the electric field and collects them on the filter bag through the combination of electrostatic action and mechanical filtration. The wet dust collector uses water mist or water spray to wet and impact the particles, so that they settle by gravity or are impacted into the water and settle.

(4) SCR and SNCR Technology. Selective Catalytic Reduction（SCR） and Selective Non-Catalytic Reduction（SNCR） technologies are mainly used to reduce nitrogen oxides (NO_X) emissions. SCR technology by the action of an accelerator, ammonia (NH_3) or urea with NO in the flue gas x A reduction reaction occurs and is converted to nitrogen and water. SNCR technology is through the injection of ammonia or urea at high temperature and other reagent, so that it with the flue gas NO_X Rapid chemochemical reaction, thereby reducing NO_X Emissions.

(5) Waste heat recovery technology. Waste heat recovery technology improves energy efficiency by capturing and reusing waste heat in the flue gas of heating boilers. This includes using a heat exchanger to transfer heat from the flue gas to the incoming water or other media that need to be heated to reduce energy consumption and greenhouse gas emissions.

The above are several common flue gas treatment technology solutions, each of which has its own unique advantages and scope of application. In specific applications, it is necessary to select a suitable combination of technologies based on actual conditions and needs to achieve more efficient flue gas treatment and environmental protection. In short, the flue gas treatment technology solution selects different technical solutions for treatment according to different flue gas components and emission concentrations to achieve the purpose of protecting the environment and reducing pollutant emissions.

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Flue gas denitrification technology program. Flue gas denitrification technology can be divided into dry method and wet method according to whether water is added during the denitrification process and the dry and wet state of the product. Traditional dry denitrification mainly includes selective catalytic reduction technology (SCR), selective non-catalytic reduction technology (SNCR), activated carbon method, electron beam irradiation method and pulse corona method, etc.; traditional wet denitrification mainly includes liquid phase absorption method and oxidation absorption method, etc. The following will specifically discuss common flue gas denitrification technologies and compare and analyze some of the characteristics of the above technologies.

Selective Catalytic Reduction technology (SCR). SCR technology is based on ammonia, liquid ammonia, urea and other reducing agents, supported by metal oxides as catalysts, NH_3 selectively catalyzed the reduction of NO_X to N_2 and $H_2O(g)$ on the catalyst surface without O_2 oxidation in the flue gas. The main reactions involved in this technology are shown in (4.1) to (4.4).

$$NH_2CONH_2 \rightarrow 2NH_3 + HNCO \quad (4.1)$$

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O \quad (4.2)$$

$$4NH_3 + 2NO_2 + O_2 \rightarrow 3N_2 + 6H_2O \quad (4.3)$$

$$2NO + 2HNCO + 1/2O_2 \rightarrow 2N_2 + 2CO_2 + H_2O \quad (4.4)$$

The above three denitrification reducing agents can reduce the emission concentration of NO_X in the flue gas, and their commercialization is relatively mature, and they all need to fully atomize the NH_3 generation source through the spray gun, and then spray into the corresponding temperature area in the furnace. The difference lies in the NH_3 generation source and corresponding supporting facilities [115]. Table 4.1 describes the quantity, efficiency, reliability and safety of the three denitration reducing agents [116].

Since the 1950s, some countries have begun to conduct research on SCR technology. In 1950, the American Eegelhard Company first proposed SCR and applied for an invention patent in 1959. Japan took the lead in completing the industrial application of SCR in 1979. Germany and the United States introduced Japanese technology in 1984 and 1993 respectively and established China's first coal-fired denitrification equipment.

Table 4.1 – Analysis and comparison of characteristics of three denitrification reducing agents

Reductant	Main equipment	Denitration efficiency	Ammonia escape	System reliability	System security
Ammonia liquor	Ammonia discharge pump and other supporting facilities, centrifugal pump (ammonia supply pump), air compressor, compressed air tank, metering and distribution facilities, spray gun, etc	70%-80% denitration efficiency is related to the ammonia spray point, in the temperature range of 800-900°C, the reaction effect is the best, the flue gas residence time is above 0.5s, to ensure the effective denitration reaction time.	Due to different boiler types, tonnage and operating conditions, the amount of ammonia escape cannot be compared. However, under the same working conditions, the amount of ammonia escape is the highest when urea is the reducing agent, the second when ammonia water is the reducing agent, and the least when liquid ammonia is the reducing agent.	The system with ammonia water as reducing agent has fewer equipment, fewer control points and higher reliability.	Ammonia has no explosive performance, the leaked ammonia is harmful to human body, and the safety is high
Urea	Lifts, centrifugal pumps (urea pumps), air compressors, compressed air tanks, heating motors, metering and distribution facilities, spray guns, etc	70%-75% urea solution is not a direct reactant, and some by-products will be generated during the pyrolysis process, which is less efficient than ammonia water.		Urea as a reducing agent system equipment is the most, the control system is more complex, the reliability is poor.	Urea is non-toxic and harmless, and does not have explosive properties, and the highest safety. It is often used in situations with high safety requirements, such as central heating boiler denitration system.
Liquid ammonia	Liquid ammonia discharge equipment, ammonia storage tanks, spray facilities, air compressors, compressed air tanks, metering and distribution facilities, spray guns, etc	More than 80% liquid ammonia, as a high concentration of ammonia-free water, produces a relatively high concentration of NH_3, and its denitrification efficiency is higher than that of ammonia and urea.		Compared with ammonia, the system of liquid ammonia as a reducing agent needs at least one more evaporator, spray system, and usually needs to be equipped with a fan that provides diluted air, and reliability is second.	Liquid ammonia is dangerous goods, low concentration of ammonia has a stimulating effect on mucous membranes, high concentration of ammonia will cause damage to human tissues, the concentration of 16%-25%, in case of open fire will burn and explosive. Secondly, the transportation and storage of liquid ammonia have certain risks.

Currently, more than 90% of the thermal power units in the United States, Japan and Germany use SCR denitrification technology. Among the coal-fired flue gas denitrification units put into operation in China, SCR technology accounts for 95% [117]. The SCR process flow is shown in Figure 4.1.

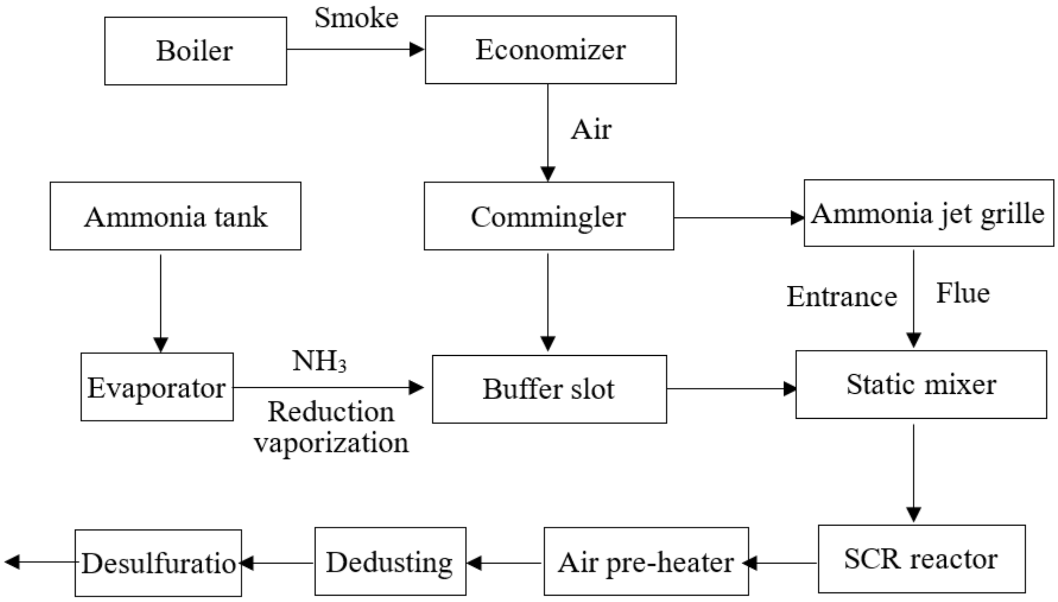


Fig. 4.1 – The technological flow chart of SCR

In order to ensure that the NO_X emission concentration meets the standard, SCR denitrification technology is often used in conjunction with SNCR denitrification technology. The difference between SCR and SNCR is that the denitrification catalyst is added and the reaction temperature is reduced. As the core component of the SCR system, the catalyst needs to be arranged separately in the reactor. The catalyst can be divided into honeycomb type, plate type, and corrugated plate type according to the type. The three types of catalysts can meet the requirements of flue gas SCR denitrification. Due to the different molding methods, application scopes, and structures, their commercial applications are different. Table 4.2 compares the characteristics and application scopes of the three catalysts.

SCR denitrification technology mainly uses high-temperature, cellular vanadium and titanium catalysts [118], which V_2O_5-WO_3(MoO_3)/TiO_2 have high activity and good anti-SO_2 performance in the temperature window of 280-420°C.

Table 4.2 – Comparison of the characteristics of three catalysts

Catalyst type	Formed structure	Picture	Formed structure	Process characteristics		Applicable flue gas condition	Market share
				Advantage	Disadvantage		
Cellular catalyst	Extrusion, coating molding, honeycomb carrier, circulation area of about 80%		Extrusion, coating molding, honeycomb carrier, circulation area of about 80%	Large contact surface, long life, wear resistance, easy regeneration	High density, not easy to disassemble	Suitable for various flue gas conditions	> 60%
Plate catalyst	The stainless steel mesh is used as the catalyst module carrier, the surface is coated with the carrier and active components, and the flow area is about 85%		The stainless steel mesh is used as the catalyst module carrier, the surface is coated with the carrier and active components, and the flow area is about 85%	Stainless steel NetEase in disassembly, easy to regenerate	Low life, poor wear resistance	Clean flue gas	About 30%
Corrugated plate catalyst	The corrugated ceramic/fiberglass board is the carrier, the surface is loaded with active components, and the flow area is about 85%		The corrugated ceramic/fiberglass board is the carrier, the surface is loaded with active components, and the flow area is about 85%	The density is small and the contact surface is medium	Easy to accumulate dust and clog	Clean (low dust content) smoke	< 10%

With the large-scale use of vanadium titanium catalysts in SCR, its toxic inactivation, relatively narrow temperature window and the active component V_2O_5 is highly toxic and other shortcomings have become increasingly apparent, so relevant scholars began to develop new efficient, low-cost, low-pollution vanadium free catalysts. At present, the development of new catalysts at home and abroad mainly focuses on Ce, Cu, Fe and Mn catalysts supported by TiO_2, Al_2O_3, activated carbon and zeolite, but most of them stay in the laboratory stage. Xiao et al. [119] pointed out that Ce group is a kind of catalyst that is expected to replace V_2O_5-WO_3/TiO_2, and studied the mechanism of H_2O and SO_2 promoting Ce/TiO_2 to reduce NO at high temperature. Ye et al. [120] prepared CeO_2-MoO_3/TiO_2 by co-precipitation method, impregnation method and sol-gel method, and found that the catalyst prepared by sol-gel method had the widest reaction temperature window (250-475°C). Zha et al. [121]

developed a novel W-doped mesoporous TiO_2 catalyst supported by Mn and Ce mixed oxides. The study showed that NO conversion rate of MnCeW/m-TiO_2 could reach more than 95% when the reactor space speed was 40000 h^{-1} and the temperature was 140-340 ℃, and the experiment demonstrated that the addition of W was helpful to enhance the catalytic performance. Jin et al. [122] studied the reaction of NO removal by adding Pr to CeO_2/Al_2O_3, and the results showed that when Pr/Ce molar ratio was 0.10 and airspeed was 5000 h^{-1},290-450℃, the average removal rate was over 90%, and the highest denitrification rate was 98.17% at 360 ℃.

Table 4.3 lists the modification or improvement experiments of catalysts with V_2O_5 as the active component and TiO_2 as the carrier conducted by experts and scholars in recent years, which not only provides theoretical basis and laboratory data support for improving the denitration efficiency of SCR, but also provides reference for the commercial application of the improved catalyst.

SCR occupies an important position in flue gas denitrification technology due to its advantages such as high denitrification efficiency and the most mature technology. However, the high investment cost of vanadium-titanium catalysts and solid waste pollution cannot be ignored. Regenerating the discarded vanadium-titanium catalysts by water washing, thermal reduction, acid solution and other methods [123] can effectively reduce solid waste pollution and reduce investment costs, achieving a win-win situation for environmental and economic benefits. In the future, the development of SCR catalysts will still focus on the widespread application of vanadium-titanium catalysts and the in-depth research on their regeneration methods, supplemented by the vigorous development of green and low-cost vanadium-free catalysts.

Table 4.3 – List of experimental studies on improvement of vanadium and titanium catalysts

№	**Catalyst**	**Active ingredient carrier**	**Additive**	**Catalyst forming method**	**Result**		**Application situation**
					Advantages	**Disadvantages**	
1	V-Mo	TiO_2	Fe_2O_3	Impregnation method	Improve the reduction performance and acidity of the catalyst	Poisoning the catalyst	Laboratory stage
			Cr_2O_3	Impregnation method	The pore structure of catalyst has little effect	With more surface acid content, reducing denitration efficiency	
			Sn	Blending pyrolysis method	It has higher reducing performance, acidic energy, denitrification activity, mercury oxidation efficiency and more chemisorbed oxygen content	/	
			Zn	Impregnation method	A suitable H_2SO_4 solution can remove the loaded Zn	The catalyst performance of denitration catalyst is reduced	
			Nb	Impregnation method	It can effectively inhibit the acidity and reducibility of catalyst caused by Na poisoning, and improve the denitrification performance	/	
			Silica sol	Impregnation method	Improve the wear resistance of the catalyst, increase the specific surface area of the catalyst, and promote the dispersion of active components	The reducing and acidic properties of the catalyst were reduced	
2	V_2O_5	TiO_2	Br	Sol-gel method, impregnation method	At the reaction temperature of 120-240℃, VTiBr2.0 catalyst has the best activity and has anti-sulfur activity	/	Laboratory stage
3	V_2O_5/WO_3	TiO_2	NiO、NiTiO₃ → NiO、$NiTiO_3$	Coprecipitation	/	Ni component infiltrates into V_2O_5-WO_3/TiO_2 catalyst in an improper way and has toxic effect on it	Laboratory stage
			CuO	Sol-gel method and impregnation method	Improve the performance of denitration catalyst	/	
			Ce	Coating method	The denitrification activity is significantly increased at the medium and low temperature of 180-260℃, and the active temperature window is obviously widened	/	
4	V_2O_5	TiO_2	K and As	Vapor deposition and wet impregnation	When potassium and arsenic coexist, the degree of deactivation of the catalyst shows an "enhanced effect".	When potassium ion exists alone, the denitrification activity of catalyst decreases	Practical application
	V_2O_5	TiO_2-SiO_2	NH_4VO_3 and Hydroxypropyl methyl cellulose（HPMC）	Drip glue coating method	The catalyst performance of denitration catalyst was improved and the consumption of vanadium was reduced	/	Laboratory stage

Selective Non-catalytic Reduction Denitration Technology. SNCR process technology is a non-catalytic reduction technology. Urea or ammonia and other reducing agents are directly injected at the flue gas temperature of 850-1100℃ at the boiler outlet. Under high temperature, ammonia reacts with nitrogen oxides in the flue gas to reduce nitrogen oxides and reduce the concentration of nitrogen oxides.

SNCR technology has a short construction period and simple construction. It does not require the replacement of induced draft fans, requires little investment, is insensitive to changes in coal types, has a medium denitrification efficiency, and is suitable for the transformation of old boilers in China. The disadvantage of this technology is that the denitrification efficiency is low and ammonia escape is prone to occur. Therefore, in terms of flue gas denitrification, the use of SNCR technology alone is subject to some restrictions.

No catalyst is used in the denitrification process, and NH_3 escape is 10-15ppm. When the reducing agent is injected into the furnace, because the reduction reaction of NO_x only occurs between 850℃ and 1100℃, the reaction temperature of the reducing agent is one of the key factors for the reduction efficiency. The optimal reaction temperature is 950℃; the key to the successful implementation of SNCR technology is that the reducing agent must be injected into the most effective temperature range in the furnace, and the total time of the reactants staying in the reactor should be controlled as much as possible, so that the reducing agent can be dispersed and mixed with the flue gas at the most appropriate temperature, so as to maximize the utilization efficiency of the reducing agent and control the minimum ammonia escape.

Compared with SCR technology, SNCR has relatively low investment and operating costs and occupies less space, but the denitrification efficiency is not high, and it is not easy to control ammonia escape.

Using safe urea reducing agent, no liquid or solid waste is generated, easy to install, and takes up very little space; NO_X removal efficiency is not high, only 25-50%; low investment and low operating cost.

When applying SNCR denitrification technology, the following two issues should be noted:

(1) The utilization rate of ammonia in the SNCR process is not high. In order to achieve the emission effect, a large amount of ammonia may be added, which is easy to form ammonia escape.

(2) The boiler efficiency is reduced. The injection of a relatively low temperature reducing agent may cause the furnace temperature to drop, resulting in incomplete combustion, increasing the CO content, and increasing the incomplete combustion loss.

Activated carbon adsorption denitrification method. Activated carbon has a developed microporous structure, a large specific surface area and abundant surface functional groups. It is a good adsorbent, catalyst and catalyst carrier. Activated carbon is used to adsorb and remove nitrogen oxides in flue gas. The essence of its main removal principle is that activated carbon adsorbs NO in flue gas on the surface through a series of catalytic oxidation processes, and then oxidizes it to generate NO_2 under the action of oxygen. At the same time, activated carbon as a catalyst can greatly reduce the activation energy of the reaction between NH_3 and NO_X, effectively improving the flue gas denitrification rate [124-126]. The advantage of the activated carbon adsorption method is that there is no problem of wastewater and waste residue. At the same time, activated carbon can also absorb and remove some heavy metal pollutants in flue gas. It also has some disadvantages, such as the large amount of activated carbon adsorbent used and the low utilization rate. At the same time, activated carbon is easy to adhere to the pipe wall, causing pipe blockage [127,128]. Knoblanch K et al. [129] reported the use of activated coke as an adsorbent and catalyst, and NH_3 as a reducing agent to remove SO_2 and NO_X from flue gas. During the experiment, it was found that activated coke can not only adsorb SO_2 and convert it into H_2SO_4, but also catalyze NH_3 to reduce NO to generate N_2. The best experimental results show that the SO_2 removal rate can reach 95%, and the NO conversion rate can reach more than 80%.

Plasma method. The plasma flue gas desulfurization technology was first proposed by the Japanese company Zahara in 1970. Two years later, they conducted a joint research on this technology with the Japan Atomic Energy Research Institute. The principle is that under the action of an external electric field, high-energy electrons are generated to bombard pollutants such as SO_2 and NO_X in the flue gas, causing them to undergo a series of complex physical and chemical reactions such as ionization, dissociation and excitation, and finally NO_X is converted into harmless N_2 [130-131]. According to different plasma generation methods, plasma methods mainly include electron beam method, pulse corona method and barrier dielectric discharge method.

The electron beam method can desulfurize and denitrify at the same time, with a desulfurization effect of more than 80%, and has strong adaptability to flue gas composition fluctuations. However, the high energy consumption and complex system structure of this method have not been solved, which has limited its promotion and use.

There are also many studies on the pulse corona method, but there has been no demonstration and application in engineering [132,133]. Barrier dielectric discharge method is currently a hot research topic, and the main research direction focuses on the selection of reducing agents and catalysts, as well as the design of reactors. Studies have shown [134] that when CO and H_2 are used as reducing agents, the reduction reaction has a high requirement for reaction temperature in the absence of a catalyst. Under weak oxidation and weak reduction conditions, the denitrification efficiency is about 40%; under strong reduction conditions, it can reach more than 90%.

Ozone oxidation absorption denitrification method. Ozone oxidation absorption denitrification is to add ozone to the flue gas, so that it is fully mixed with the flue gas to react chemically, and the NO in the flue gas is oxidized into high-valent nitrogen oxides such as NO_2, N_2O_3, etc. After being sprayed with water, it is dissolved in water to form nitric acid.

After the flue gas is dusted, it is oxidized into high-valent NO_X by O_3 in the NO_X generator. The flue gas containing high-valent NO_X enters the absorption tower and contacts with NaOH solution to generate $NaNO_3$. The flue gas after the reaction is purified by the demister and discharged into the atmosphere; part of the reaction mixture is pumped into the tower by the circulation pump for recycling, and part is discharged by the pump to obtain $NaNO_3$ crystals after filtration, separation, and drying. The principles involved in this process are shown in formulas (4.5)-(4.9).

$$O_3+NO \rightarrow NO_2+O_2 \tag{4.5}$$

$$O_3+2NO_2 \rightarrow N_2O_5+O_2 \tag{4.6}$$

$$NO_2+H_2O \rightarrow HNO_3+NO \tag{4.7}$$

$$N_2O_5+H_2O \rightarrow 2HNO_3 \quad (4.8)$$

$$HNO_3+NaOH \rightarrow NaNO_3+H_2O \quad (4.9)$$

The main factors affecting oxidation are the ratio of the molar number of O_3 to NO and the oxidation time. Practice has shown that the oxidation rate of NO increases with the increase of O_3/NO. The ozone denitrification rate is relatively high, reaching up to 85% or more. The main factors affecting ozone denitrification are: ozone amount, reaction time, mixing degree of ozone and flue gas, etc. Practice has shown that the oxidation residence time of ozone in flue gas is a key and important factor.

The flue gas enters the NO oxidation reaction zone through the rectifier, and the NO in the flue gas reacts with ozone. After that, the flue gas enters the packed absorption tower. Nitrogen oxides are oxidized to high-valent and water-soluble N_2O_5, and the product formed after washing is HNO_3. The product is discharged to the acid storage tank and discharged for utilization or sale after reaching a certain concentration.

Liquid phase absorption methods

(1) Alkaline solution absorption method. The alkali solution absorption method uses a neutralization reaction to react an alkaline solution with NOx to generate nitrates and nitrites. Commonly used alkaline solutions include NaOH, Na_2CO_3, ammonia water or calcium hydroxide. During the absorption process, NO_2 first dissolves in water to generate nitric acid and nitrous acid, and then nitrous acid and nitric acid react with the alkali solution to neutralize the acid.

The traditional process of alkali solution absorption is: the flue gas enters the three-stage series absorption tower in sequence, and the alkali solution enters the absorption tower in reverse. When the circulating alkali solution concentration of the first-stage absorption tower drops to 5g/L, the absorption liquid can be released. The released absorption liquid is recycled after evaporation, crystallization, and separation. The by-products sodium nitrate and sodium nitrite can be used as finished products or sold.

The biggest advantage of the alkali solution absorption method is that it can recover NOx and convert it into nitrite and nitrate products, which can generate certain economic benefits while purifying the flue gas. However, the purification efficiency of the alkaline solution absorption method is not high, and the efficiency of alkaline solution in absorbing NO under normal pressure is very low. It is generally only applicable to NOx waste gas containing more than 50% NO_2, and is not suitable for denitrification of combustion flue gas.

(2) Acid solution absorption method. The solubility of NO in water is very low, while its solubility in dilute nitric acid is much higher. Exhaust gas containing nitrogen oxides can be treated with dilute nitric acid solution.

The process flow of the dilute nitric acid absorption method is as follows: the nitric acid used as an absorbent is first blown away with air to remove the dissolved NO_X in it. The NO_X tail gas coming out of the nitric acid absorption tower enters the lower part of the absorption tower and contacts with the absorption liquid (15%-30% bleaching nitric acid) in countercurrent for physical absorption. The nitric acid that absorbs NO_X is heated and enters the bleaching tower, where it is bleached with air, and then cooled to 20°C by a cooler for recycling. The bleached NO_X is returned to the nitric acid absorption tower for recycling. The characteristics of the denitrification treatment by the dilute nitric acid absorption method are simple process flow, convenient operation, and easy control; the disadvantages are large acid circulation volume and high power consumption.

Comparison of common flue gas denitration schemes (Table 4.4)

Table 4.4 – Results of a comparative analysis of common flue gas denitration schemes

Technology	Denitrification rate	Principle	Advantages and disadvantages	Application status
SCR	80%-90%, up to more than 95%	NO_x was reduced to non-toxic N_2 and H_2O by amino reducing agent under catalyst	The desulfurization rate is high and the technology is the most mature; However, the investment and operating costs are high, the catalyst is expensive and easy to be poisoned, and accompanied by ammonia escape.	Widely used; More for the coal-fired power industry with large emissions
SNCR	> 60%, up to about 75%	NO_x is directly reduced to N_2 and H_2O by amino reducing agents	Mature technology, low investment and operating costs; Ammonia escape is more serious	Widely used; Mostly used in small and medium coal, cement and other industries
Adsorption method	80% to 90% (Activated Carbon)	The adsorbent (activated carbon/coke, molecular sieve, etc.) catalyzes and adsorbs NO_x and then reduces it with amino, and the adsorbent is regenerated by heating or steam	Simple equipment, can be coordinated desulfurization; However, the adsorption amount is small, the amount of adsorbent is large, and the regeneration is frequent.	Activated carbon / coke process is widely used. Suitable for industries with lower emissions
Plasma method (electron beam, pulse corona)	＞70%	The free radical produced by high-energy electrons is used to oxidize NO to NO_2, and then into NH_3 and H_2O (g) to produce ammonium nitrate	Simple operation, can cooperate with desulfurization and dust removal, no waste residue and waste water; But high energy consumption	Not widely applied
Oxidation absorption method	> 85%, up to 90% (O_3 method)	NO is oxidized to NO_2 by gaseous phase (O_3, Cl_2, etc.) or liquid phase ($NaClO_2$, $HClO_3$, H2O2, etc.) oxidants, and then removed by re-absorption	O_3 method is simple to operate, but the investment and operation cost are high; $NaClO_2$, $HClO_3$ expensive, easy to corrode equipment; H_2O_2 is easy to decompose and consumes a lot of light	Only O_3 oxidation method is widely used, mostly used in petrochemical, carbon and other industries; The rest are not widely used in industry
Liquid phase absorption method	＞90%	Use common water, lye (caustic soda, lime milk, ammonia, etc.) or acid (nitric acid, sulfuric acid, etc.) to absorb and remove NO_x	The by-product with high concentration of nitric acid/(nitrite) nitrate can be recycled. However, a high NO_2/NO is required	Widely used; It is mostly used in high-concentration NO_2 exhaust industries, such as nitric acid plants

The transformation and upgrading of traditional flue gas denitrification technologies such as SCR and SNCR has enabled coal-fired power, cement and chemical industries to achieve ultra-low emissions. Although such technologies are mature in industrial applications and have high removal efficiency, each method has its own uniqueness, limitations, advantages and disadvantages. In actual engineering applications, only by combining its characteristics and selecting and combining corresponding methods can the denitrification effect reach an ideal level [135]. In the future, flue gas denitrification technology will widely apply existing high-efficiency SCR, SNCR and ozone oxidation absorption technologies, vigorously develop integrated desulfurization and denitrification technologies such as adsorption and plasma methods, and explore flue gas denitrification technologies suitable for the country's regional characteristics [136].

Flue gas desulfurization technology scheme.

Dry desulfurization technology. Dry desulfurization refers to the use of adsorbents, granular or powdered absorbents, catalysts, etc. to remove sulfur from boiler flue gas.

The advantages of dry desulfurization are: relatively low corrosiveness, no wastewater and waste acid, less heat loss after desulfurization and higher flue gas temperature. Disadvantages are: low desulfurization efficiency and slow reaction speed. Currently, the main dry desulfurization technologies are:

(1) Carbon desulfurization technology. Carbon desulfurization uses a carbon-based absorbent as a desulfurizer to catalytically oxidize SO_2 into SO_3, which then reacts with H_2O to produce dilute H_2SO_4. Activated carbon, carbon fiber, etc. are commonly used desulfurizers. Saturated activated carbon is regenerated by steam heating or water, and low-concentration H_2SO_4 or high-concentration SO_2 can be generated at the same time [137]. This technical solution can effectively control the emission of SO_2 in flue gas and realize the recycling of sulfur resources. The main by-

products are H_2SO_4, liquid SO_2 and sulfur. The main advantages of carbon-based desulfurization technology are: low equipment investment and operating costs, small space required, and strong economic competitiveness.

(2) Electron beam desulfurization technology. The electron beam desulfurization process has a very high technical content, precise equipment, large equipment investment, and high equipment operation and maintenance costs. At present, this technology is only in trial operation in a few enterprises. If it is to be promoted and applied, there are still many technical difficulties that need to be tackled through scientific research. SO_2 in flue gas is highly corrosive to precision instruments, so most of the equipment in this process needs to be treated with anti-corrosion. At the same time, due to the strong penetration and penetration of the electron beam of the electron irradiation reaction device, the on-site environment requirements are relatively high.

(3) In-furnace calcium spraying-tail activation desulfurization technology. The in-furnace calcium spraying-tail activation desulfurization technology is currently a widely used desulfurization method. The main technical principle is to spray lime or limestone directly into the boiler, stay in the furnace for a short time, and quickly react chemically at high temperature to achieve the purpose of removing sulfur oxides in the flue gas. The main reaction process is the absorption of SO_2 by CaO, the reaction generates $CaSO_3$, and is oxidized by O_2 to $CaSO_4$. The reaction equation is as follows (4.10)-(4.14):

$$CaCO_3 \rightarrow CaO + CO_2 \quad (4.10)$$

$$CaO + SO_2 \rightarrow CaSO_3 \quad (4.11)$$

$$CaCO_3 + SO_2 \rightarrow CaSO_3 + CO_2 \quad (4.12)$$

$$2CaSO_3+O_2\rightarrow 2CaSO_4 \quad (4.13)$$

$$2CaO+2SO_2+O_2\rightarrow 2CaSO_4 \quad (4.14)$$

The main advantages of furnace calcium injection desulfurization technology are: cheap and easy to obtain desulfurization raw materials, low basic equipment investment, and low operation and maintenance costs. The ash produced during the dry desulfurization process can be mixed with cement for use. The main component of the ash produced by the CFB-FGD dry desulfurization process is $CaSO_3\cdot 1/2H_2O$, which has a retarding effect when mixed with cement. The research results show that within a certain range of desulfurization ash addition, the greater the addition, the better the retarding effect.

Semi-dry desulfurization technology. The main working conditions of semi-dry desulfurization technology are: lack of water, small unit capacity, and low sulfur content in coal. In the actual implementation process, this technology is usually combined with dust removal technology. The semi-dry method is more effective than the dry method [138-140].

<u>(1) Spray drying desulfurization</u>. The advantages of spray drying desulfurization are: high desulfurization efficiency, about 85%; no wastewater discharge; and lower investment cost than wet process technology. The main disadvantages are: unscientific use of desulfurizers, resulting in poor reaction performance. Spray drying accumulates solid particles attached to the tower wall, causing pipeline blockage. High-speed spray equipment has large losses, frequent replacement, and high production costs. In actual production, by increasing the research and development of high-efficiency

desulfurizers and increasing the recycling of ash systems [141,142], these technologies have been successfully applied in the latest SDA devices.

(2) Activated coke desulfurization process. The principle of the activated coke desulfurization process is to use physical and chemical adsorption to achieve the purpose of adsorption and removal of SO_2. SO_2, H_2O and O_2 are first adsorbed on the surface of activated coke, and then react through the active sites in the pores to generate sulfuric acid and sulfate. The main advantages of this process technology are: low water consumption, high desulfurization efficiency, high strength, low investment and operating costs, etc.

(3) NID semi-dry desulfurization process. This technology uses calcium oxide or calcium hydroxide as a desulfurization adsorbent, and is a combined process that integrates desulfurization and dust removal. Water is added to humidify the absorbent, which reacts with SO_2 in the flue gas to generate calcium sulfite. The reacted absorbent then enters the dust removal system for collection, and finally mixes with fresh absorbent for recycling. Reaction temperature, relative humidity, and the amount of recycled materials added are all important parameters that affect the desulfurization effect. The main advantages of this method are: high desulfurization efficiency, SO_2 removal rate of more than 90%, short water evaporation time, and small device footprint.

(4) Circulating suspended semi-dry desulfurization process. Circulating suspended semi-dry desulfurization uses electrostatic dust removal. After the dust is removed, it is fully contacted and reacted with the absorbent in the absorption tower in the desulfurization device. The dust in the flue gas is removed and then passed through the bag filter for dust removal. After the flue gas is humidified, the desulfurization effect will generally be better.

Wet desulfurization technology. More than 90% of China's power plants use wet flue gas desulfurization (WFGD) technology. Depending on the desulfurizer used, there are currently four common technical routes for wet desulfurization technology: limestone/lime-gypsum method, magnesium oxide method, ammonia method and double alkali method [143-146].

(1) Limestone/lime-gypsum wet desulfurization process. The main principle of this technology is to use limestone or lime as a desulfurization absorbent, crush the limestone into powder, mix it with water to form an absorption slurry, and react with the flue gas in the absorption tower. With the auxiliary effect of oxidizing air, SO_2 reacts with calcium carbonate to form gypsum. The development history of this process is as follows: The first generation of limestone/lime-gypsum wet desulfurization technology began to be industrialized in the 1970s. It was found that the equipment was prone to corrosion and scaling. Through the progress of the second generation of desulfurization in the early 1980s and the third generation of desulfurization technology in the 1990s, the desulfurization process technology was more perfect in the 20th century, the desulfurization efficiency was significantly improved, the scaling and clogging phenomena were basically controlled, and the investment cost of basic equipment was reduced. The process technology is more mature and has been widely promoted and applied. At present, the main features of this process are: the process technology route is increasingly mature, the system is simplified, and the equipment is reduced, but there are still problems such as high investment cost and easy to cause secondary pollution.

(2) Magnesium oxide desulfurization process. This technology is currently second only to calcium desulfurization technology [147-153] and was successfully

developed by Chemico-Basic of the United States. The technical principle is basically the same as the lime-gypsum wet method, except that magnesium oxide is used as the desulfurizer instead of lime. In the desulfurization tower, magnesium hydroxide slurry reacts chemically with SO_2 in the flue gas to produce water and magnesium sulfite, and magnesium sulfite reacts with oxygen to produce magnesium sulfate. Because magnesium sulfate is soluble in water, the possibility of pipeline blockage is greatly reduced. my country is rich in magnesium resources, which provides a solid raw material guarantee for the implementation of magnesium oxide wet desulfurization technology. Therefore, magnesium oxide flue gas desulfurization is an environmentally friendly and efficient desulfurization technology with a very broad application prospect.

(3) Ammonia desulfurization process. The main advantages of this technology are: simple technical principle, high absorption efficiency, and wide application [154-158]. It uses the reaction between urea and ammonia to remove SO_2 and form ammonium sulfate. The process flow of this technology is: nitrogen or air mixed with a certain volume of SO_2 enters from the bottom of the desulfurization tower; ammonia water is sprayed downward from the top of the desulfurization tower, and fully contacts with the mixed gas flowing from bottom to top on the surface of the packing in the desulfurization tower to absorb SO_2 in the mixed gas. The gas after SO_2 is removed is discharged from the top of the desulfurization tower into the atmosphere; the mixed liquid that has absorbed SO_2 is discharged from the bottom of the absorption desulfurization tower, and the product ammonium sulfate is obtained through concentration, dehydration, drying, etc.

(4) Double alkali method. The main principle of this technology is to directly inject sodium hydroxide or sodium carbonate solution (first alkali) into the

desulfurization tower to remove SO_2 in the flue gas by washing. The desulfurization products produced by the reaction are sodium bisulfite and sodium sulfite. It reacts with lime or limestone (second alkali) to produce sodium hydroxide, which is recycled in the desulfurization tower [159]. Its main advantages are low investment cost, low scaling and clogging in the tower, and low liquid-gas ratio. The main disadvantages of this technology are: poor process controllability, difficult regeneration of the product sulfate, need to supplement alkali to meet the operating effect, and the quality of gypsum is reduced due to the presence of sulfate.

Comparison of common flue gas desulfurization solutions. Common flue gas desulfurization methods and their characteristics are shown in Table 4.5.

Table 4.5 – Comparison of common flue gas desulfurization solutions

Project	**Wet limestone-gypsum process**	**Flue gas circulating fluidized bed**	**Ammonia process**	**Calcium injection in furnace-tail activation method**	**Spray drying process**
1	2	3	4	5	6
Technological route	Wet process	Dry process	Wet process	Dry process	Semidry
Application of coal	Middle and high sulfur coal	Middle and low sulfur coal	Middle and low sulfur coal	Medium and low sulfur	High Middle Low Sulfur
Technology maturity	Higher	high	game	in	high
Domestic Technology Mastery	Introduction of technology, cooperation with foreign countries, self-development	Introduction of technology, cooperation with foreign countries, self-development	Introduction of technology, cooperation with foreign countries, self-development	Cooperation with foreign countries and self-development	Introduction of technology, cooperation with foreign countries, self-development
Sulfur removal efficiency%	>95	>90	>94	>70	>90
Molar ratio of calcium to sulfur	1.05	1.2	0.02	2.5	1.4
Desulfurizing agent	Limestone	Lime Powder (Cao)	Ammonia	Stone powder (CaCO3)	Lime Powder (CaO)
Desulfurizer utilization rate%	Higher	Higher	Higher	Low	Medium

Continue Table 4.5

1	2	3	4	5	6
Desulphurization products and properties	Gypsum, wet	Ash, dry	Ammonium salt, wet	Ash, dry	Ash, dry
Desulfurization product utilization	good	general	good	difficult	general
Occupation of land	Large	Less	Less	Medium	Medium
Initial investment in conventional unit costs (%)	High	Medium	Low	Medium	Medium
Localization rate	Lower	High	High	High	High
Water consumption (t/h)	Large	Less	Less	High	Less
Power consumption (kW)	Large	Less	Less	Many	Less
Personnel required to operate	Many	Less	Less	High	Less
Amount of desulfurization per year	Large	Large	Large	Less	Large
Annual Operating Cost of Desulfurization Unit	High	Low	Low	High	Low
Technological process	Complex	More complex	Simple	Relatively simple	Complex
Equipment resistance (pa)	>1500	High	<500	High	high

Comparing the common flue gas desulfurization methods: wet limestone-gypsum method, flue gas circulating fluidized bed ammonia method, furnace calcium injection-tail activation method, spray drying method. From the analysis in the table, it can be seen that the off-furnace desulfurization technology using the limestone-gypsum wet desulfurization process is expected to reduce the sulfur dioxide emission concentration to below 32mg/Nm^3, which meets the latest environmental emission requirements.

4.2 Energy-saving technologies for heat energy consumption and production facilities

In recent years, with the continuous increase in global energy consumption and the increasing impact on the environment and climate, energy shortages and environmental pollution have attracted more and more attention, and energy consumption and carbon emissions have become important issues worldwide. In the past few decades, the demand for heat energy in industry and production facilities has continued to increase, and these facilities are the main source of energy consumption and carbon emissions. In terms of heat energy consumption and production facilities, the rational implementation of energy-saving technologies has become a common task for all countries. In the field of heating, the use of energy-saving technologies has become an important way to reduce heat energy consumption and pollutant emissions. Therefore, the rational implementation of energy-saving technologies has become a vital task.

Energy-saving technologies for heat energy consumption. Traditional heating methods mainly use gas, coal and other energy sources for heating. The combustion of fuels will produce a large amount of waste gas and wastewater, causing environmental pollution. In order to solve this problem, we can use the following energy-saving technologies:

(1) The use of intelligent temperature control systems can control the temperature in the room to avoid excessive heating and cooling, thereby reducing heat energy consumption.

(2) Optimize the pipeline system and use insulation materials to insulate the pipeline to reduce the transmission loss of heat energy.

(3) The use of heat pump technology can effectively convert low-temperature heat energy in the environment into high-temperature heat energy and recycle indoor waste heat, thereby achieving energy-saving effects.

(4) The use of renewable energy such as solar energy and ground source heat for heating reduces fuel consumption and promotes sustainable development.

In addition, in terms of heat energy consumption, the rational use of energy-saving boilers, heat exchangers, and pipeline insulation materials, strengthening equipment maintenance management, and regularly inspecting and cleaning coolers, radiators and other components can effectively reduce energy consumption. In addition, scientifically setting up temperature control systems, regularly checking water quality, and cleaning dirt are also effective measures to reduce energy consumption.

Energy-saving technologies for production facilities. In terms of production facilities, we can adopt the following energy-saving technologies:

(1) Equipment energy saving. In the design and use of heating facilities, use advanced heating equipment, repair and maintain the equipment, reduce the failure rate, strengthen management, and achieve maximum energy utilization efficiency and incremental emission reduction goals.

(2) Circular economy. Utilize waste heat, waste gas, waste water, and waste residue resources in heating facilities, promote the construction of energy-saving and environmentally friendly heating facilities, realize clean and stable gas supply, and promote the comprehensive reduction of energy consumption in heating systems.

(3) Building energy conservation. In the design process of buildings, energy-saving technologies are adopted, such as selecting energy-saving building materials, selecting windows and doors for insulation, to achieve the dual goals of energy conservation and environmental protection.

At the same time, energy-saving equipment and technologies are adopted as much as possible, such as changing fan-type air conditioners to nozzle-type air conditioners made of new materials, and heat pump technology can also replace traditional boilers and other equipment. At the same time, production emission control is carried out to reduce the emission of pollutants, which not only improves product competitiveness and reduces environmental pollution, but also saves energy costs for enterprises. For long-term sustainable development goals, it is necessary to improve the efficiency of heating energy and equipment, reduce heat energy consumption, and vigorously develop renewable energy to achieve sustainable energy utilization and sustainable environmental protection.

By adopting energy-saving technologies in the heating field, heat energy consumption and pollutant emissions can be effectively reduced, and environmental protection and sustainable development goals can be achieved. In the process of implementing energy-saving technologies for thermal energy consumption and production facilities, it is necessary to comprehensively consider the specific situation and take a variety of measures to make energy-saving measures operational and implementable, so as to achieve the best energy-saving effect and contribute to global energy conservation and emission reduction.

In short, the reasonable implementation of energy-saving technologies is not only a requirement of the enterprise itself, but also a social responsibility to protect the environment and save energy. Enterprises can achieve green and low-carbon development and contribute to global sustainable development by improving energy efficiency, adopting energy-saving production technologies, and choosing renewable energy. The reasonable implementation of energy-saving technologies is essential to reduce energy consumption and carbon emissions, improve the competitiveness of facilities and achieve sustainable development. The application of energy-saving technologies in thermal energy consumption and production facilities can significantly reduce energy waste and environmental load. Although there may be some challenges in practice, through continuous investment and technological innovation, we can continuously improve energy-saving technologies and promote their application worldwide.

4.3 Description of a real object for experimental research into the method of rational implementation of energy-saving technologies

Technical characteristics of the selected research object. To study the effectiveness of the Rational Implementation of Energy-Saving Technologies (RIEST) approach, we selected a real object (RO) in the field of education, namely the 6th Teaching and Sports Complex of Vinnytsia National University of Technology (hereinafter referred to as RO), located at 95 Khmelnitsky Highway, Vinnytsia, Ukraine. The building is centrally heated by the regional boiler room of the municipal enterprise "Vinnytsia City Heat and Energy Company", which uses the design fuel-natural gas. Since its commissioning, the building has not been completely renovated, and its initial energy ecological state was evaluated based on the actual average unit energy demand value during three years of stable operation and other forecast, actual annual and long-term energy demand indicators (Fig. 4.2-4.3).

Fig. 4.2 – Panoramic view of the main facade of RO

Fig. 4.3 – Location of RO in the area:

Image taken from Google Map, geographic coordinates 49.231887,28.411204

RO is a two-storey building built in 1986, with a basement as a heating area and a loft covering the entire building, with a total heating area of 2282 m². The building is not listed as a cultural heritage monument and is included in the National List of Immovable Monuments of Ukraine. There is no separate project documentation.

Technical documents show that the building volume of RO hydropower station is 8024.0 m^3, with a centralized hot water supply system set up according to individual projects. It has not been used since the 1990s, is not suitable for work, and has been partially demolished. The public needs of the RO building are provided by the following types of fuel and energy: thermal energy in the form of hot water to provide heating needs; Electricity to meet the needs of hot water supply and internal lighting. The foundation of the building is made of concrete foundation blocks with a thickness of 400 mm. The basement is located under the entire building of RO, has heating, and is used as a shooting range and air-raid shelter. The overlapping part of the basement heating space and the ground floor rooms is a multi-layer hollow reinforced concrete slab, covered with a layer of particle board in the office and a layer of colored polished concrete in the public corridor. The floor of the heated basement consists of a layer of concrete on gravel or natural crushed stone with a thickness of 100 mm and a layer of expanded clay concrete on expanded clay sand with a thickness of 80 mm.

The total area of the external walls is 980.7 m^2, made of solid ceramic tiles with cement mortar, covered with a layer of cement plaster on the outside using the "fur coat" technique and a layer of lime mortar on the inside; the total thickness of the wall structure is 0.424 m. The heat transfer resistance of the external walls is 0.65 $(m^2 \cdot K)/W$, which does not meet the current DBN B 2.6-31 [160] standard-the resistance should not be less than 4.0 $(m^2 \cdot K)/W$.

The roof is a partially built-up, partially sloped unheated attic covered with galvanized siding of metal profiles, built-up coating, with a total area of 333.8 m^2. The roof structure is: the outer side of the wooden rafters is supported by wooden rafters, on which a layer of roofing material and a layer of mineral wool insulation with a thickness of 100 mm are laid, and the insulation layer is covered with a layer of roofing material and galvanized siding of metal profiles. Starting from the middle of the house, the combined covering is surrounded by a layer of DPV. The heat transfer resistance reduction value of the existing combined coating is 1.80 ($m^2 \cdot K$)/W, which does not meet the requirements of the current standard – the resistance is not less than 7.0 ($m^2 \cdot K$)/W. The total area of the attic covering is 312.4 m^2, it is cold, not ventilated with the outside air, covered with reinforced concrete slabs, and there is no insulation layer in any design.

The transparent buildings available in RO have different structural designs and can be grouped according to the following types: PVC profiles, single-chamber glass units 4M1-18-4M1 (gas medium-air), total area 11.4 m^2; existing translucent structures, heat transfer resistance reduction 0.32 ($m^2 \cdot K$)/W; wood paired double-glazing, total area 175.1 m^2; existing transparent structures, heat transfer resistance reduction 0.39 ($m^2 \cdot K$)/W; hollow glass blocks with dimensions of 244×244×98mm and total area 29.8 m^2; existing translucent structures with heat transfer resistance reduction of 0.33 ($m^2 \cdot K$)/W, which does not meet the current standard resistance requirement of at least 0.90 ($m^2 \cdot K$)/W.

The existing external doors have different designs and can be grouped according to the following types: made of aluminum profiles, single-glazed, total area 6.3 m^2; existing translucent structures with reduced heat transfer resistance of 0.17 ($m^2 \cdot K$)/W; wooden, total area 7.1 m^2; existing external doors with reduced heat transfer resistance of 0.31 ($m^2 \cdot K$)/W; steel non-insulated, total area 1.5 m^2; existing external doors with reduced heat transfer resistance of 0.17 ($m^2 \cdot K$)/W, which does not meet the current standard requirement of resistance of at least 0.70 ($m^2 \cdot K$)/W.

The heating system inside the house is of two-pipe design with low distribution of heat carriers and is equipped with M-140 cast iron sectional heating radiators without thermostats. There are no individual heating point in the building that can automatically control and regulate the consumption of thermal energy. The indoor heating system is designed to operate in the temperature range of 95-70 °C, and the actual operating temperature range in the past 3 years is close to 80-60 °C. There is no actual heating cost for the centralized hot water supply and forced ventilation demand in the building. The hot water supply is provided by electric boilers with a capacity of 80 and 100 liters installed locally at the hot water use site. The average annual actual thermal energy consumption of RO in the past 3 years is 385.5 MWh. The building site is not used during holidays.

The results of the comprehensive evaluation of the current technical and eco-economic status of a specific object are determined using the method of EST phased implementation [161] and the mathematical model of the RIEST method implemented in PC. Table 4.6 lists the evaluation results of RO before the implementation of environmental protection and energy-saving measures.

Table 4.6 – Current Energy Ecological Assessment Results of RO

S_{ha},	q,	q_s,	v_{fuel},	m_{CO2},	m_{NOx},	f_{heat},
m^2	MWh	kWh/m^2	thou. m^3	tone	kg	thou. EUR
2282	385.5	168.9	38.7	20.6	127.7	19.1

Table 4.7 presents the results of the assessment of the environmental and economic potential of RO energy efficiency after the implementation of recommended environmental protection and energy conservation measures.

Table 4.7 – Results of the assessment of the possibility of increasing the energy efficiency of RO

δp,	**Δq,**	**$Δq_s$,**	**$Δv_{fuel}$,**	**$Δm_{CO2}$,**	**$Δm_{NOx}$,**	**f_{save},**
%	MWh	kWh/m^2	thou. m^3	tone	kg	thou. EUR
67	260	113.9	35.3	18.7	116.4	16.5

Energy-saving technologies and measures used for the study of the effectiveness of the RIEST method. A series of measures for saving resources and energy were formed for the described social infrastructure goals, the RIEST method was chosen for implementation and will be used in the course of further experimental and computational studies. The following are the 8 different energy saving measures adopted.

Reduction of excessive heating costs through the envelope of buildings and pipes.

(1) Thermal modernization of buildings. This is a measure involving integrated engineering performance, the result of which is an increase in the thermal resistance of the building envelope [162], namely: external walls, composite roofs, attic coverings, ground and first floor floors above unheated volumes; replacement of transparent structures and entrance doors with modern structures – the aim is to improve their tightness and heat transfer resistance to a level that meets the requirements of DBN B.2.6-31 [160].

(2) Upgrading of pipe networks. Modernization of pipes of general heating systems, heating and hot water systems, and stop valves on specific pipes. This measure includes: replacing existing insulation materials on pipes and stop valves on them [163] or replacing specific pipes with pre-insulated pipes in their entirety to increase their heat transfer resistance to a level that meets the requirements of current regulatory documents.

(3) Renovation of hot water systems. Replace obsolete heat exchanger models with modern compact plate heat exchangers with appropriate thermal capacity, and

insulate them compulsorily in the future [164]. The design features of plate heat exchangers have higher thermal efficiency and smaller external surface, which can reduce technically unavoidable heat energy losses compared to obsolete heat exchanger models.

Rational use of building thermal energy.

(4) Implementation of "smart technology" in heating systems. This is a measure involving the use of regulating devices and control mechanisms of heating equipment in the building's internal heating system, which allows the heating system to be controlled in the absence of personnel by maintaining the internal air temperature at a given level or changing a specified temperature during the day in automatic mode according to a given algorithm [165].

(5) Recovery of waste heat from ventilation systems. Modernization of ventilation systems is carried out by introducing heat recovery devices in the total exchange ventilation system. The designated modernization involves the reconstruction of existing ventilation systems by introducing heat recovery units [164]. Such heat recovery equipment allows reducing energy costs for heating and cooling, since heat energy is separated from the air exhausted from the building through the exhaust ventilation system and transferred to the air supplied to the building through the supply air system.

Technologies for improving heat sources.

(6) Replacing obsolete fuel boilers with efficient gas boilers. Reconstruction of existing boiler rooms or construction of new boiler rooms, introducing energy-saving gas condensing or solid fuel boilers. Reconstruction involves replacing obsolete fuel-using equipment with modern gas condensing or solid fuel boilers with higher efficiency [166]. At the same time, during the reconstruction, the combustion process

should be automatically controlled and the temperature of the coolant at the outlet of the boiler room should be automatically adjusted according to weather conditions.

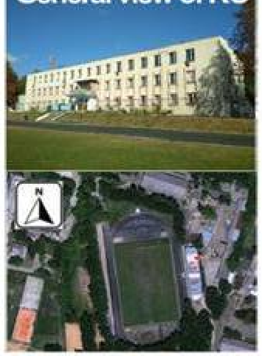
(7) Implementation of solar energy systems (HS) as an alternative heat source for heating. Equipment that allows converting solar heat into heat energy of heat carriers, which ensures the operation of hot water supply of the studied object without the use of traditional fuels [167]. Under the climatic conditions of Ukraine, solar energy systems can guarantee 40-60% of the annual demand for hot water supply. The specified technology can be completely environmentally neutral, as long as the electrical energy consumed by the pumps and the automatic control of the specified system is generated by environmentally friendly sources (wind turbines and solar panels).

(8) Use of heat pumps as an alternative heating source. Heat pumps allow you to capture low latent heat of the environment (external air, flowing groundwater or surface water, soil) through the evaporation of a refrigerant in an external circuit [168]. The specified technology consumes electricity, but can reduce the total energy consumption for meeting the heating system and hot water supply needs by 3-5 times, depending on the type of heat pump and the efficiency of the device.

4.4 Verification of the method of rational implementation of energy-saving technologies

Figure 4.4 shows the general view and geographical location of the research object-the sports building of VNTU, as well as a fragment of the information map of the effectiveness of RIEST strategies with its (out of 4) tables. Table from above describes the current state of the research object. The specific heat energy demand of the building is 168 kWh/m^2, indicating its low level of energy efficiency. Table in the middle characterizes the energy saving potential of the research object, determined as a result of the energy audit. The indicator of the dimensionless generalized ecological and economic effect – 67% indicates the possibility of reducing the thermal energy consumption of this building by 2/3 as a result of the implementation of the recommended EST complex (and obtaining other effects indicated in the table due to this). Table below presents the results of the distribution of recommended EST by stages A, B, and C, the values of the payback periods and costs of EST and stages, as well as the results of assessing the effectiveness of each ET and stage. The research results presented in this table show the following: 5 energy-saving technologies are recommended for implementation – thermal modernization of the roof and ventilation system (together constitute stage A), smart home technology and thermal modernization of walls (together constitute stage B), the use of an alternative source of thermal energy – heliosystem (constitute stage C), the total estimated investment volume is 88.3 thousand EUR, the total economic effect of the implementation of EST (determines the self-financing potential of the research object) is 16.5 thousand EUR, the payback period of strategy 1 is 5.4 years.

Figure 4.5 presents the results of a comparative analysis of EST implementation strategies at the research object-the sports building of VNTU: a table with the results of calculations, which is the 4th table of the information map of the effectiveness of RIEST strategies, as well as graphic images of the most effective and least effective RIEST strategies.



Current energy and environmental status of the research object

S_{ha}, m²	Q, MWh	Q_s, kWh/m²	V_{fuel}, thou. m³	M_{CO2}, tone	M_{NOx}, kg	C_{heat}, ths.UAH	C_{heat}, ths. EUR
2282	385,5	168,9	38,7	20,6	127,7	830,9	19,1

Energy efficiency potential of the object under study

δP, %	ΔQ, MWh	ΔQ_s, kWh/m²	ΔV_{fuel}, ths. m³	ΔM_{CO2}, tone	ΔM_{NOx}, kg	ΔC, ths.UAH	ΔC, ths. EUR
67	260	113,9	35,3	18,7	116,4	714,6	16,5

Effectiveness of ESTs recommended for implementation

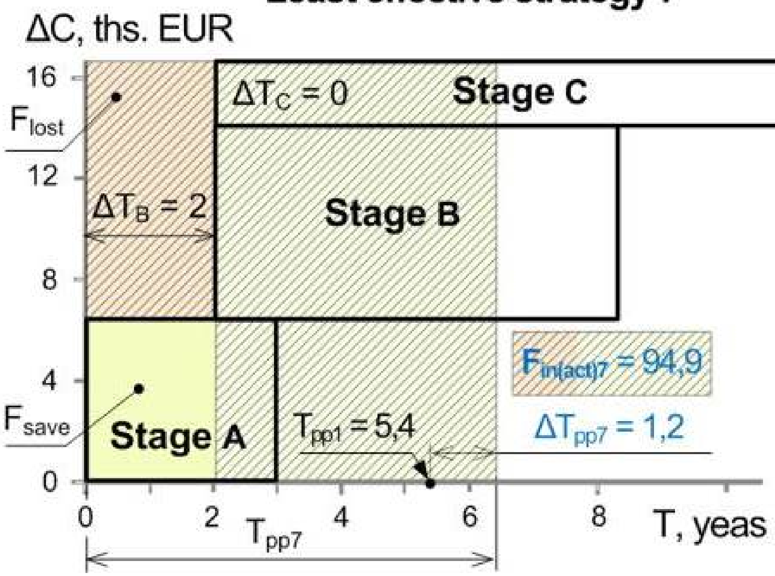
Stage	NP_{EST}	EST	Efficiency parameters of EST: ΔQ, MWh	ΔQ_s, kWh/m²	ΔV_{fuel}, ths. m³	ΔM_{CO2}, tone	ΔM_{Nox}, kg	ΔC, ths. EUR	ΔP, %	$F_{in(cal)}$, ths. EUR	T_{pp}, years
A	1	TM (r)	52,4	23	7,12	3,8	23,5	3,3	14	7,8	2,3
	2	TM (vs)	51,4	22,5	6,99	3,7	23	3,3	13	12,0	3,7
	Total A stage		**103,8**	**45,5**	**14,11**	**7,5**	**46,5**	**6,6**	**27**	**19,8**	**3,0**
B	3	SH	16,4	7,2	2,22	1,2	7,3	1,0	4	5,5	5,3
	4	TM (w)	107,3	47	14,57	7,7	48,1	6,8	28	43,8	6,4
	Total B stage		**123,7**	**54,2**	**16,79**	**8,9**	**55,4**	**7,9**	**32**	**49,3**	**6,3**
C	5	HS	32,4	14,2	4,39	2,3	14,5	2,0	8	19,2	9,7
	Total C stage		**32,4**	**14,2**	**4,39**	**2,3**	**14,5**	**2,0**	**8**	**19,2**	**9,7**
A,B,C	**Total A,B,C stage**		**259,9**	**113,9**	**35,29**	**18,7**	**116,4**	**16,5**	**67**	**88,3**	**5,4**

Fig. 4.4 – Results of the assessment of the current state and energy saving potential of the research object - the building of the educational institution

Results of comparison of RIEST strategies

RIEST Strategy	Delay periods for the start of stage, years			Financial flows to implement strategies, ths. EUR					Criteria for the effectiveness of RIEST strategies						
	ΔT_A	ΔT_B	ΔT_C	F_{lost}	F_{save}	ΔF	$F_{in(cal)}$	$F_{in(act)}$	$\delta F_{in(act)}$, %	ΔT_{pp}, years	Δq, EUR/MWh	Δv_{fuel}, EUR/th.m^3	Δc, EUR/EUR	Δm_{NOx}, EUR/kg	Δp, EUR/%
0		∞		16,6/year	0,0	-16,6/year	0	16,6/year	-18,7/year	∞	0	0	0	0	0
1			0	0,0	0,0	0,0		88,3	0,0	0	0,34	2,50	5,4	0,76	1,32
2	0	0	1	2,0	14,5	12,5		75,8	14,2	0,1	0,29	2,15	4,6	0,65	1,13
3			2	4,0	23,2	19,2		69,1	21,7	0,2	0,27	1,96	4,2	0,59	1,03
4			0	9,9	6,6	-3,3		91,6	-3,7	0,6	0,35	2,59	5,6	0,79	1,37
5	0	1	1	11,9	21,1	9,2	88,3	79,1	10,4	0,7	0,30	2,24	4,8	0,68	1,18
6			2	13,9	29,8	15,9		72,4	18,0	0,8	0,28	2,05	4,4	0,62	1,08
7			0	19,8	13,2	-6,6		94,9	-7,5	1,2	0,37	2,69	5,8	0,82	1,42
8	0	2	1	21,8	27,7	5,9		82,4	6,7	1,3	0,32	2,33	5,0	0,71	1,23
9			2	23,8	36,4	12,6		75,7	14,3	1,4	0,29	2,14	4,6	0,65	1,13

Least effective strategy 7



Most effective strategy 3

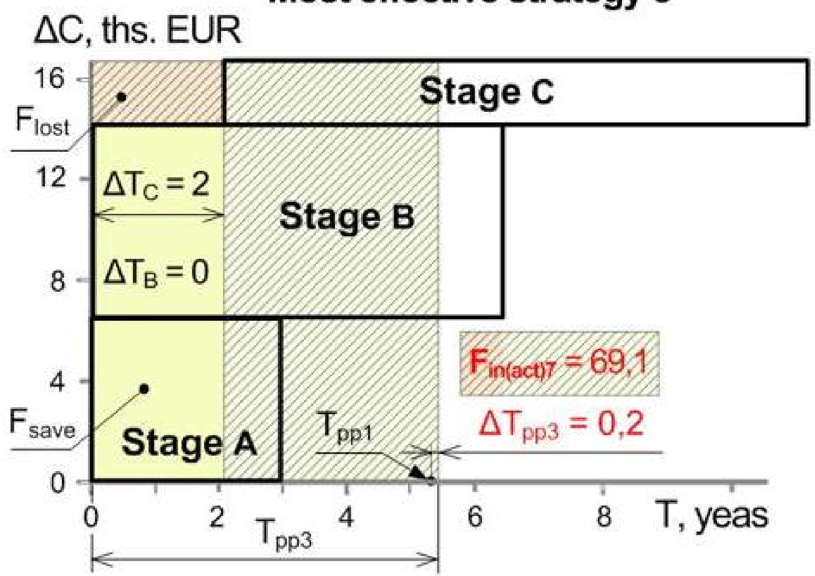


Fig. 4.5 – Results of research on the effectiveness of RIEST strategies

The figure presents the results of a comparative analysis of EST implementation strategies at the research object – the sports building of VNTU: a table with the results of calculations, which is the 4th table of the information map of the effectiveness of RIEST strategies, as well as graphic images of the most effective and least effective RIEST strategies. The results presented in the table allow us to draw the following conclusions:

(1) Indefinite continuation of the current state of the research object, which corresponds to strategy 0, is the most unprofitable option for its further use; at the same time, excess thermal energy is consumed annually in the amount of 260 MWh, fuel-35.3 ths m^3, economic costs-16.5 ths EUR, the environment is polluted by 18.7 tons of CO_2 and 116.4 kg of NO_x;

(2) When implementing strategies 1-9, the actual financial costs vary in the range from 69.1 thousand EUR to 94.9 thousand EUR or from 78.3% to 107.5% compared to the estimated value of the investment volume-88.3 thousand EUR, which is spent when implementing strategy 1;

(3) The most effective is strategy 3 with delay periods for stages B and C - 0 years and 2 years, respectively; the generalized ecological and economic effect is 21.7%, savings in investment resources - 19.2 ths EUR, the increase in the payback period of investment costs compared to strategy 1 is insignificant and amounts to 0.2 years (a graphic representation of the process of implementing this strategy is shown in the lower right figure);

(4) The least effective is strategy 7 with the delay periods of stages B and C - 2 years and 0 years, respectively; the generalized ecological and economic effect is -

7.5%, the overspending of investment resources is -6.6 thousand EUR, the increase in the payback period of investment costs compared to strategy 1 is significant and amounts to 1.2 years (a graphic representation of the process of implementing this strategy is shown in the lower left figure).

Analysis of the graphic images of both strategies allows us to establish the reason for the effectiveness of one and the unprofitability of the other: in strategy 3, the financial flow of saved resources (yellow) is the maximum among all strategies and significantly greater than the flow of losses (pink), and in strategy 7, on the contrary, the flow of saved resources is the minimum among all strategies and less than the flow of losses.

Conclusions to the Chapter 4

1. This chapter systematically explores the application effects and implementation paths of energy-saving and environmental protection technologies in the field of heating by combining theoretical analysis with empirical research. The study takes the 6th Teaching and Sports Complex of Vinnytsia National Technical University as a typical case, and uses the RIEST method to comprehensively evaluate its energy-saving potential. The evaluation results verify the effectiveness of the RIEST method in practical applications. It is worth noting that the study particularly emphasizes the economic advantages of the phased implementation strategy, among which strategy three achieves the best energy-saving effect at the lowest cost (69,100 euros), while strategy seven increases the cost to 94,900 euros due to improper

implementation timing. This finding provides an important reference for investment decisions in subsequent energy-saving renovation projects.

2. In terms of energy-saving technologies for heat production and consumption facilities, the study analyzes in detail the application effects of key technologies such as intelligent temperature control systems, heat pump technology, pipeline insulation optimization, and the use of renewable energy such as solar energy. The intelligent temperature control system significantly improves energy utilization efficiency through time-sharing temperature control and remote monitoring functions; the heat pump technology achieves energy cascade utilization by recycling low-grade heat energy; and pipeline insulation optimization effectively reduces the loss during heat transmission. The comprehensive application of these technologies not only reduces the energy consumption of the heating system, but also greatly improves the operating efficiency of the system. The study specifically pointed out that when implementing these energy-saving technologies, it is necessary to select the most suitable technology combination according to the specific characteristics and usage requirements of the building in order to achieve the best energy-saving effect.

3. In terms of flue gas treatment technology, the study systematically sorted out the current mainstream denitrification and desulfurization technology solutions. In the field of denitrification technology, the advantages and disadvantages of the two mainstream technologies of SCR (selective catalytic reduction) and SNCR (selective non-catalytic reduction) were analyzed. Although SCR technology has high denitrification efficiency (up to more than 95%), it has problems such as high investment cost and easy poisoning of catalysts; while SNCR technology has a lower

cost, but its denitrification efficiency is relatively limited (60%-75%). By comparing the characteristics of different reducing agents (ammonia water, urea, liquid ammonia), the study provides targeted technical selection suggestions for heating facilities of different sizes. In terms of desulfurization technology, the study compared the applicable conditions of wet, dry and semi-dry desulfurization technologies. Among them, although the wet limestone-gypsum process has a high desulfurization efficiency (>95%), it has problems with equipment corrosion and wastewater treatment; while the dry desulfurization is simple to operate, but the efficiency is relatively low. These technical comparisons provide a scientific basis for heating companies to choose the pollution control solution that best suits their own conditions.

4. The study also pays special attention to the interactive relationship between technological innovation and institutional environment. By analyzing the differences in the application of different technical solutions in Europe, the United States and Asian countries, the guiding role of regulatory policies on technology selection is revealed. For example, the strict carbon emission policies of European countries have promoted the widespread application of SCR technology, while Asian countries are more inclined to choose SNCR technology suitable for the characteristics of centralized heating. This perspective of technology-policy co-evolution provides important inspiration for the formulation of subsequent policy recommendations. At the same time, the study also pointed out that with the continuous improvement of environmental protection requirements, traditional single pollution control technologies have been difficult to meet the requirements of "ultra-low emissions", and more attention needs to be paid to

the research and development and application of multi-pollutant coordinated control technologies in the future.

5. The research results of this chapter lay a solid foundation for the improvement suggestions to be proposed in Chapter 5. Based on the empirical research results of the RIEST method, the phased implementation strategy can be further optimized in the future, especially in terms of investment timing and cost control; and the comparative analysis of various energy-saving and environmentally friendly technologies provides a basis for the formulation of differentiated technology promotion policies. In addition, the synergy between technology and policy revealed by the study also reminds us that we need to fully consider the feasibility of technology implementation when making policy recommendations. These findings will directly guide the formulation of recommendations in Chapter 5 on reducing boiler emissions, improving energy efficiency, and maximizing economic benefits. In particular, they provide empirical support for improving the RIEST method, so that it can better balance economy and operability while considering technical feasibility, thereby promoting the development of heating systems in a more efficient, low-carbon, and environmentally friendly direction.

CHAPTER 5 RECOMMENDATIONS ON THE USE OF RESEARCH RESULTS TO SOLVING MUNICIPAL ENERGY PROBLEMS

In the previous chapters, we have put forward a series of suggestions for solving urban environmental problems, covering green energy, sustainable development theory, enforcement of regulations and energy-saving and environmental protection technologies. These suggestions provide a comprehensive blueprint for urban environmental protection, but we recognize the complexity and diversity of urban environmental problems, and more specific and refined measures are needed to solve challenges in different areas.

In this chapter, we will focus on urban environmental problems in the heating sector and put forward targeted suggestions to reduce the impact of harmful emissions from boiler plants on environmental pollution, while increasing the rational use of energy and fuel resources to achieve maximum economic benefits. The heating sector plays a key role in urban energy consumption and environmental pollution, so it requires special attention and innovation. We will explore how to adopt efficient and environmentally friendly technologies and strategies in the heating sector to improve urban environmental quality, reduce energy consumption, reduce carbon emissions, and provide urban residents with a more livable living environment.

Through the suggestions in this chapter, we hope to provide practical guidance for urban decision makers, environmental protection agencies and related industries to help them take innovative measures in the heating sector to achieve the dual goals of sustainable urban development and environmental protection. These suggestions will provide more specific and professional directions for solving urban environmental problems and bring a clean and sustainable living environment to the city's future.

5.1 Recommendations on the practical use of the improved RIEST method

Although this paper only studies one building, the 6th Teaching and Sports Complex of Vinnytsia National Technical University, Ukraine, this research method can be applied to other larger buildings or building complexes. In this study, we selected the best strategy for implementing energy-saving measures. This can also be done for other larger sports venues and other buildings.

The Fig. 5.1 presents recommendations for the use of the improved RIEST method in complex technical systems "producer-consumer" of thermal energy in the form of a schematic diagram, which consists of separate logically connected fragments with arrows indicating these connections. The energy modernization facility (EMF) is considered as a single technical system, which includes: heat energy consumers-buildings or groups of buildings, heat transportation equipment-pipelines, energy producers-installations or a complex of installations that generate heat (boilers of various types, heat pumps, solar systems, etc.). Increasing the energy and environmental efficiency of this technical system is carried out based on the results of an energy audit of its elements by implementing a set of recommended energy-saving technologies: thermal modernization of building envelopes and pipelines, use of boilers with increased energy efficiency, alternative energy sources, smart home technologies, etc. In this case, it is necessary to follow the recommended order of implementation of these technologies, which is indicated in the diagram by the corresponding numbering (in blue circles)-from the consumer to the producer of thermal energy.

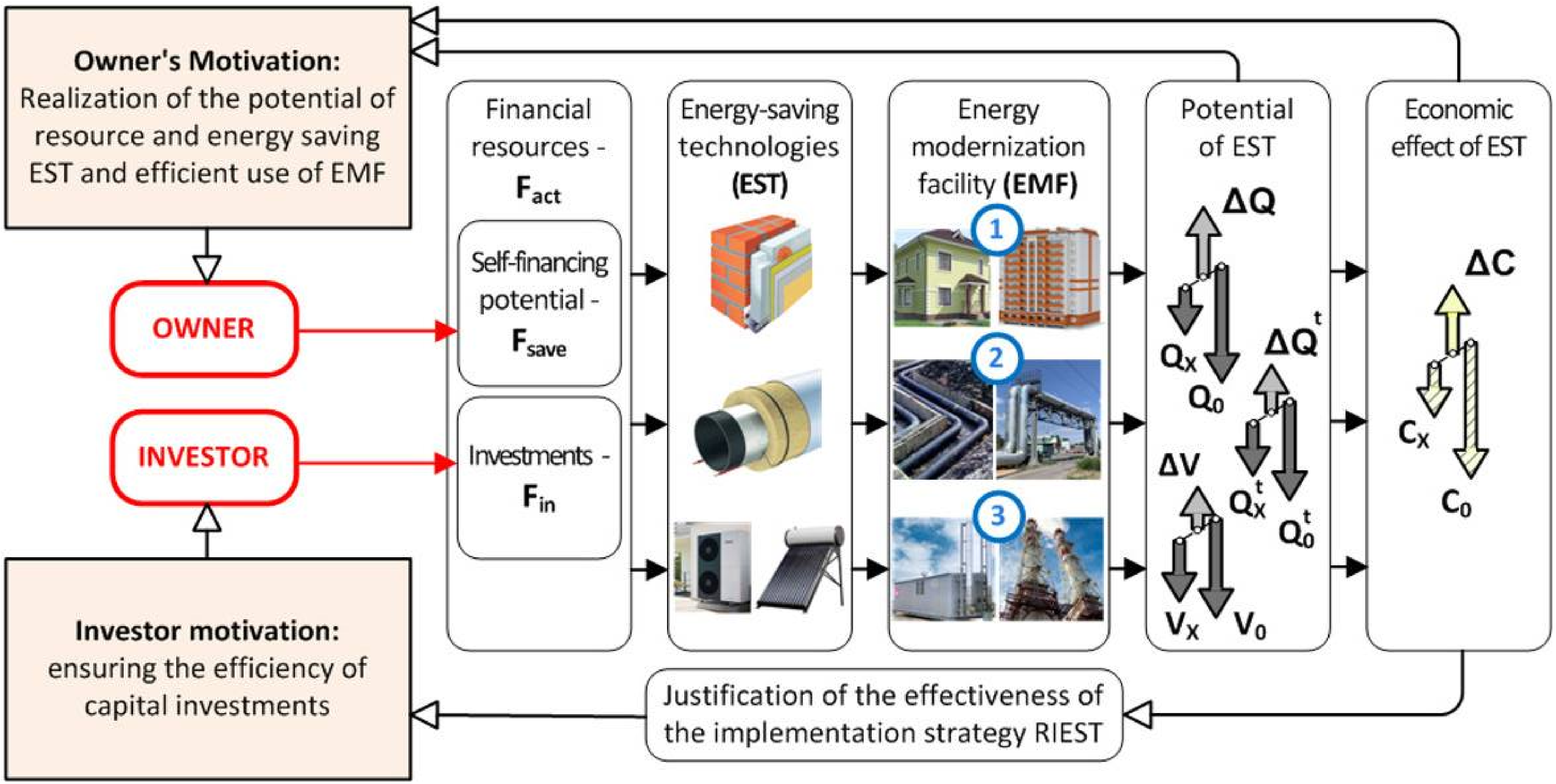


Fig. 5.1 – Recommendations for the practical use of the improved RIEST method

It is proposed to finance the process of implementing the recommended technologies in stages based on the RIEST method using 2 sources: investment resources and the self-financing potential of the EMF. As a result of the implementation of EST, environmental and economic effects are achieved: energy saving, resource saving, reduction of environmental pollution, and cost savings. When implementing ECT based on the improved RIEST method, the most investment-attractive financing strategy for this process is selected, which provides for the most effective use of the EMF self-financing potential, consisting of funds saved from the implementation of stages A and B. This approach allows us to take into account the motivations of the owner and investor, as the main participants in the process of energy modernization of the object under study (these motivations are shown in the figure). Thus, the main scientific and practical result of the dissertation research-the improved RIEST method can be used to increase the energy and environmental security of urbanized areas through economic energy modernization of both simple and large-scale technical systems-"producer-consumer" of thermal energy: from buildings to large groups of consumers and heat producers in cities and settlements.

5.2 Proposals for reducing pollution of urban areas by harmful emissions from boiler plants

With the growth of population and the continuous acceleration of urbanization, heating has become an indispensable part of urban life. However, the impact of pollutants emitted during the heating process on the environment is becoming more and more serious. In order to reduce the pollution caused by harmful emissions from boiler plants, we should reasonably introduce energy-saving and environmental protection technologies in the heating field, reduce harmful emissions from boiler plants, and achieve sustainable development of the urban environment. In order to better solve this problem, it is necessary to strengthen management and control from the following aspects.

Develop and apply high-efficiency energy-saving boilers. High-efficiency energy-saving boilers directly utilize circulating exhaust gas, steam normal pressure heating and discarded high calorific value fuels during the combustion process, and use multi-point spraying, multi-stage cooling and recycling technologies to recover energy and cleanly burn. This type of boiler can greatly reduce energy loss and reduce negative impacts on the environment. Cities can reduce their contribution to environmental pollution by introducing high-efficiency energy-saving boilers.

Promote clean combustion technology. It is necessary to accelerate the development and application of clean energy (such as wind energy, photovoltaic energy) and achieve application results in the heating field. Urban heating companies should seize the time, take advantage of the current abundant wind and light resources, and accelerate the laying of related power facilities. At the same time, the government should formulate a series of supporting policies as soon as possible, give certain financial support to local governments and enterprises, promote clean energy in the field of heating, reduce heating pollution, and improve the urban environment.

Boiler combustion is one of the main causes of environmental pollution. The promotion of clean combustion technology, such as the use of low-nitrogen combustion technology and gas combustion technology, can significantly reduce the emission of harmful gases. Nitrogen oxides are one of the main pollutants in boiler emissions. By introducing low-nitrogen oxide combustion technology, the emission of nitrogen oxides can be reduced and the harm to the environment and public health can be alleviated. Low-nitrogen oxide combustion technology is a measure to reduce the relative emission of nitrogen oxides by adding reactants during boiler combustion. By controlling the temperature and oxygen supply during the combustion process to reduce the reaction between oxygen and nitrogen, the amount of nitrogen oxides produced and the emission of nitrogen oxides can be reduced; while gas combustion technology can reduce the generation of harmful substances during the combustion process, thereby reducing the emission of such pollutants. Therefore, cities can effectively reduce the emission of nitrogen oxides and achieve the purpose of reducing air pollution by introducing this technology.

Introduction of desulfurization and denitrification technology. Desulfurization and denitrification technology is one of the important technologies for reducing the emission of atmospheric pollutants. By reducing the generation of sulfur oxides and nitrogen compounds in the boiler, the purpose of reducing emissions can be achieved. For boiler plants that are already in use, the exhaust gas can be treated by introducing desulfurization and denitrification technology to reduce the emission of harmful substances.

Strengthen flue gas treatment. Strengthen the flue gas treatment system, such as installing dust collectors and Faro mist eliminators with high-efficiency ash separation devices, and further reduce environmental pollution by treating exhaust gas. High-efficiency dust collectors can remove particulate matter in combustion exhaust gas to the greatest extent, and Faro mist eliminators can centrally treat harmful substances in flue gas.

Strengthen pollution supervision and emission control. Build environmental monitoring stations and online monitoring equipment to monitor and collect data on the emission of harmful gases in real time. Targeted emission control can effectively reduce harmful emissions from boiler plants through standardized supervision and enforcement and punishment of violations.

City governments should establish comprehensive monitoring measures, build environmental monitoring stations and online monitoring equipment, monitor and collect data on the emission of harmful gases in real time, and monitor and control the emission of pollutants from heating boilers. Monitoring can effectively understand the combustion conditions of boilers and enhance management in accordance with emission standards. By standardizing supervision and enforcement and punishing violations, a penalty system can be established for boilers that fail to meet the standards, which can effectively reduce harmful emissions from boiler plants.

The above are some specific suggestions for reducing environmental pollution caused by harmful emissions from boiler plants. Among them, clean combustion technology and desulfurization and denitrification technology are the preferred measures to reduce the emission of harmful gases; at the same time, strengthening flue gas treatment and pollution supervision and control can also improve the combustion efficiency of boiler plants and reduce pollution emissions. In the process of urban environmental protection, measures to reduce environmental pollution caused by harmful emissions from boiler plants are urgent, and should be accelerated with the joint efforts of all parties to achieve the goal of reducing pollution and improving urban air quality. At the same time, these measures have achieved a good balance between environmental protection and sustainable development, paving the way for the sustainable development of the urban green heating industry.

5.3 Proposals on increasing the rational use of energy and fuel resources

We are currently facing the problem of shortage of energy and fuel resources in the world, and the rapid development of modern cities cannot be separated from the support of energy and fuel resources. In order to maintain our economic development, we must make rational use of energy and fuel resources. Therefore, how to make rational use of these resources and reduce energy waste and environmental pollution has become an urgent problem to be solved in urban development. Here, I would like to provide some suggestions on increasing the rational use of energy and fuel resources.

First, we should strengthen the development and utilization of renewable energy. Renewable energy includes solar energy, wind energy, hydropower, etc. These energy sources have the advantages of recycling, inexhaustible and inexhaustible, have almost no pollution to the environment, and can drive industrial upgrading and create employment opportunities. With the development of technology, we have been able to obtain a lot of electricity from renewable energy sources such as sun, wind power and hydropower. These energy sources should be our priority both in terms of environmental protection and sufficient production capacity. Therefore, the government should increase its support and promotion of renewable energy, provide financial support and a series of preferential policies to encourage enterprises and individuals to invest in the construction of renewable energy.

Secondly, we need to vigorously promote the technology and awareness of energy conservation and emission reduction. Due to the shortage of our energy and fuel resources, we should fundamentally reduce our dependence on them. This means that we need to widely publicize energy-saving and emission-reduction technologies and promote them among enterprises and individuals. At the same time, the government should establish corresponding laws and regulatory mechanisms to ensure that they are widely used and followed.

Finally, we need to strengthen the supervision of the exploitation and use of fuel resources. As a country and region, we should weigh our natural resources and consider the benefits and risks of exploiting them. At the same time, we should ensure the rational use of fuel resources to avoid them being wasted or used in unnecessary areas. The government and enterprises should establish plans for fuel resource conservation and implement these plans through various means.

In addition, for traditional energy sources such as coal, oil, and gas, new technologies should be introduced through research and investment to make their use cleaner and more efficient while reducing environmental pollution. For example, coal gasification technology can be used to turn coal into clean gas. In addition, the government can also establish environmental protection incentives to encourage enterprises or individuals to develop and adopt environmentally friendly fuels and energy.

In general, if we want to maintain the speed of our economic development and protect our environment, we need to strengthen the rational use of energy and fuel resources. This means that we need to give priority to renewable energy, promote energy-saving and emission-reduction technologies and awareness, and strengthen supervision of the exploitation and use of fuel resources. We hope that through our efforts, we can contribute to the long-term utilization of energy and fuel resources. By rationally utilizing energy and fuel resources, we can achieve environmental protection and the maximum benefits of resource utilization. The government and citizens should work together to uphold the concept of "green development and sustainable development" and promote the sustainable development of cities.

5.4 Recommendations on increasing the economic efficiency of heat supply systems

Urban heating is an important guarantee for urban life, but the economic burden on enterprises and residents should not be underestimated. How to achieve the maximum economic benefits of urban heating under the premise of ensuring the quality of heating has become a problem that urban managers and heating companies must face. Through the research results of this article, some suggestions are put forward to solve this problem.

Strengthen heating management and reduce operating costs. Industrial economic scale is the key to achieving economic benefits, and the purpose is to achieve scale benefits under the guarantee of subsidy policies. The management of urban heating should be strengthened, and operating costs should be reduced by optimizing the heating network, improving heat source equipment, and determining the scope of heating. At the same time, the government should strengthen the supervision of heating, enforce standards, improve the management efficiency and level of heating companies, and reduce administrative expenses and construction costs.

Reduce heating energy consumption and improve energy utilization. Energy efficiency and energy saving have become a current trend. By adopting new technologies and new materials, optimizing equipment, reducing heating heat losses, and achieving the maximum organic utilization of energy. In the heating system, energy-saving variable frequency pumps, pipeline insulation, low-temperature chimneys and other technologies can be used to improve the efficiency of the system and reduce the energy consumption of the system. At the same time, urban heating can also use new technologies such as waste heat power generation, solar energy, wind energy, etc. to reduce dependence on traditional coal and provide sustainable development support for the urban heating system.

Promote decentralized heating. On the basis of traditional heating, introduce decentralized heating systems to better utilize boiler heat. Adhere to the combination of vertical and horizontal heating methods to improve urban heating conditions. At the same time, decentralized heating can reduce the differences in heating conditions, meet the needs of residents, form a new heating model, save a lot of costs for urban heating, and optimize household heating costs.

Strengthen policy support and encourage social capital participation. The formulation and regulation of policies should pay attention to the characteristics of the market economy, strengthen market competition, and reflect a reasonable profit model for heating companies. Strengthen policy support and encourage other social capital to actively participate in urban heating, promote the integration of market resources, form an industrial cluster effect, and effectively improve the economic benefits of heating companies.

In short, in the field of urban heating, to achieve the maximum economic benefits, it is necessary to strengthen heating management, reduce operating costs, reduce heating energy consumption, improve energy utilization, promote decentralized heating, strengthen policy support, and encourage social capital participation. Through these measures, the heating needs of residents can be better met, and a win-win situation for enterprises and residents can be achieved.

Conclusions to the Chapter 5

1. As the practical application part of the whole conducted research, this chapter systematically constructs a solution system for the green transformation of urban heating systems based on the theoretical exploration and technical verification of the first four chapters. The study first deepens the application value of the RIEST phased implementation strategy from the methodological level, and through the empirical case of Vinnytsia National Technical University of Ukraine, it confirms the great potential of this model in building energy-saving transformation, that is, the early energy-saving benefits are rolled to support the later transformation, providing a replicable implementation path for areas with limited funds. At the technical application level, the study proposes a synergistic solution combining clean combustion technology with end-of-pipe treatment for the core problem of boiler pollution control.

2. By studying urban environmental problems and their causes, effective suggestions for solving urban environmental problems are proposed. In terms of reducing harmful emissions from boiler plants, this paper recommends working on

three aspects: policy, technology and management. In terms of policy, the penalties for illegal emissions should be increased, and more stringent environmental protection policies should be formulated. In terms of technology, boiler plants should be encouraged to improve their own technology and equipment levels and adopt more environmentally friendly fuels and emission reduction technologies. In terms of management, daily supervision and management of boiler plants should be strengthened to ensure compliance with environmental laws and regulations and relevant policies. Through comprehensive management, harmful emissions from boiler plants can be reduced, thereby alleviating the pressure of urban environmental pollution. In terms of increasing the rational use of energy and fuel resources, this paper suggests that energy conservation and emission reduction activities can be carried out to improve energy utilization efficiency. In addition, the use of new clean energy such as renewable energy and new energy can also be encouraged to further reduce energy consumption and emissions. The promotion and development of clean energy is not only beneficial to environmental protection, but also can promote economic development. In terms of achieving maximum economic benefits, this paper suggests introducing ecological concepts in urban planning and construction, giving full play to the role of the ecosystem, protecting and building urban green spaces, and optimizing the urban ecological environment. In addition, urban management and services should be strengthened to improve the quality and image of the city. The quality of the urban environment directly affects the image of the city and economic development. Therefore, it is necessary to build a livable city and achieve the maximum economic benefits.

3. Urban environmental problems are not only related to people's quality of life and physical health, but also directly affect the image of the city and economic development. Therefore, in order to achieve long-term development, effective measures must be taken to solve urban environmental problems. This paper proposes three suggestions: reducing harmful emissions from boiler plants, increasing the rational use of energy and fuel resources, and achieving maximum economic benefits. These suggestions can promote the improvement of the urban environment and the upgrading of the economy, and lay a solid foundation for the sustainable development of the city. As the goals of carbon peak and carbon neutrality are advanced, these achievements will provide continuous theoretical support and practical guidance for urban heating systems to achieve a win-win situation of environmental and economic benefits.

CONCLUSIONS

The dissertation sets and solves the current scientific and applied task of increasing the efficiency of greening municipal energy systems and improving the ecological state of urbanized areas by creating and verifying an improved method for the rational implementation of energy-saving technologies at objects that consume and produce thermal energy in the municipal sector. The results of the research and work performed allow us to draw the following conclusions.

1. A comprehensive analysis of environmental problems, environmental protection and energy-saving technologies in the field of heat supply was conducted, which made it possible to assess the current state and trends in the development of centralized heat supply in different countries of the world, to systematize technologies for increasing the energy and environmental efficiency of municipal energy systems, and to substantiate the feasibility of implementing the principle of rational implementation of energy-efficient measures and technologies.

2. The method of rational implementation of energy-saving technologies in the field of heat supply has been improved by introducing new ecological and economic criteria for assessing the effectiveness of energy modernization procedures for technical systems "producer-consumer of thermal energy", the introduction of which allows for a more complete assessment of the degree of rationality of the use of investment resources when carrying out energy-efficient measures and implementing programs to improve the energy and environmental security of urbanized areas.

3. The feasibility of using and developing an information map form for multi-criteria assessment of the effectiveness of various strategies for the rational

implementation of environmental energy-saving technologies based on the criteria of the specific cost of achieved environmental, economic and generalized effects has been scientifically substantiated, which constitutes an information basis for making reasoned technical decisions regarding the choice of the most cost-effective procedures for realizing the energy-saving potential of buildings and heat supply systems.

4. A mathematical model for determining parameters and assessing the effectiveness of procedures for the rational implementation of energy-saving technologies has been further developed, which allows taking into account the losses of the integral energy-saving potential of facilities that produce and consume thermal energy in the initial and final periods of their phased energy modernization; this allows increasing the accuracy and reliability of determining the predicted environmental and economic effects.

5. The conceptual foundations of improving the energy and environmental security of municipal energy have been analyzed and systematized, which include: the main provisions of the theory of sustainable development, the principles of the recycling economy, the concept of energy modernization of urban heating networks, the justification of the feasibility of rational implementation of energy-saving and environmental protection measures in the field of heat supply, and an improved methodology for the rational implementation of energy-saving technologies in the municipal sector has been proposed.

6. A comprehensive analysis of current trends in the modernization of the sphere of state management of municipal energy was carried out in the following areas: progressive international experience in increasing the efficiency of state regulation of

urban energy systems; comparative analysis of the principles of regulation and development of municipal energy in European and Asian countries.

7. A complex of studies on the efficiency of technologies for ecological and energy modernization of building heating systems was conducted and the following results were obtained: the technologies for cleaning exhaust gases from boiler plants and energy-saving technologies for facilities that consume and produce thermal energy were systematized; the effectiveness of the method for rational implementation of energy-efficient technologies was verified and assessed at a real facility - a sports facility of an educational institution.

8. Recommendations and proposals have been developed for the practical use of the results of the research in solving municipal energy and environmental problems by applying the following measures: practical implementation of the RIEST method, technologies for reducing pollution of urbanized areas by harmful emissions from boiler plants, increasing the rational use of energy and fuel resources, and increasing the economic efficiency of heat supply systems.

9. The verification of the improved RIEST method was carried out and its practical suitability for choosing the most investment-attractive strategy for increasing the ecological and economic efficiency of the operation of the investigated object - the building of the sports complex of Vinnytsia National Technical University was confirmed. The results of the study demonstrated the possibility of increasing the energy efficiency of the studied building by 67% by implementing 5 recommended energy-saving technologies. It was established that the implementation of the strategy selected on the basis of the RIEST method allows for a significant reduction in the

required investment resources - from 88.3 ths. EUR to 69.1 ths. EUR, i.e. by 21.7%. At the same time, the following annual environmental and economic effects are achieved: reduction in thermal energy consumption by 260 MWh, reduction in fuel consumption - natural gas by 35.3 ths. m^3, reduction in CO_2 and NO_x emissions into the atmosphere by 18.7 tons and 116.4 kg, respectively, reduction in economic costs for heating the building by 16.5 ths. EUR.

10. Based on the results of the conducted research, recommendations have been developed to increase the versatility and expand the scope of application of the improved RIEST method in technical systems "producer-consumer of thermal energy" and their elements of different types, which include: objects that consume thermal energy - public and industrial buildings and groups of buildings, objects that transport thermal energy - heat networks of centralized and autonomous heat supply systems, objects that produce thermal energy - boiler plants, alternative and renewable energy sources, namely: high-efficiency gas boilers, heat pumps, solar systems, etc. The recommendations take into account the motivation of the owners of the studied buildings and heat supply systems and investors who ensure the implementation of the energy modernization strategy of these facilities.

11. The results of the dissertation research were implemented in the educational processes of training students of Vinnytsia National Technical University, who study in specialties 101 - "ecology" and 183 - "environmental protection technologies" and the production activities of the private enterprise "INTEREKO", which is confirmed by the relevant acts of implementation.

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APPENDIX A

LIST OF PUBLISHED WORKS BY DISSERTATION TOPIC

Articles in periodical scientific publications indexed in the Scopus database:

1. **Zhang Le**, Polyvianchuk Andrii. Development of coal flue gases denitrification technologies in China. *Environmental problems*. Vol. 10, No. 1, 2025. – P. 88-96. DOI: https://doi.org/10.23939/ep2025.01.088.

2. **Zhang Le**, Polyvianchuk Andrii. Application of denitration technology in flue gas treatment of coal-fired boiler. *Environmental problems*. Vol. 10, No. 2, 2025. – P. 88-96. DOI: https://doi.org/10.23939/ep2025.02.110.

Articles in professional publications of Ukraine, category «Б»:

3. **Чжан Ле**, Полив'янчук А.П. «Очищення димових газів вугільних котлів від оксидів азоту. аналіз проблем та перспектив». *Вісник ВПІ*, вип. 2, с. 39–44, Квіт. 2025. DOI: https://doi.org/10.31649/1997-9266-2025-179-2-39-44.

Individual collective monographs

4. **Zhang Le**. Analysis of world experience in state regulation and reform of the thermal power industry. Technical, agricultural and applied sciences as mechanisms for the development of human self-knowledge: collective monograph. *International Science Group*, Boston. 2024. – P. 368-383. ISBN: 979-8-89480-692-1. DOI: https://doi.org/10.46299/ISG.2024.MONO.TECH.4.

5. **Zhang Le**. Theoretical basics of ensuring sustainable development of urban heat supply. Global transformations of social development. *Видавництво «Новий курс»*, Харків. 2024. – P. 144-154. ISBN:978-617-7886-66-1, DOI: https://doi.org/10.61718/mon, URL: https://www.newroute.org.ua/wp-content/uploads/2024/11/globtran.pdf.

Co-authored collective monograph

6. **Zhang Le**, Polyvianchuk Andrii. Analysis of energy-efficient and environmental technologies in the field of heat supply. Science, technology and innovation in the context of global transformation: Scientific monograph. *Baltija Publishing,* Riga. 2024. – P. 96-121. ISBN: 78-9934-26-499-3. DOI: https://doi.org/10.30525/978-9934-26-499-3-5.

Proceedings of scientific conferences which confirm the validation of research results

7. Polyvianchuk Andrii, **Zhang Le**. Analysis of technologies for improving the environmental performance of central heating boilers. *Proceedings of the V International Scientific and Practical Conference «Prospects of modern science and education»*, Stockholm, Sweden, February 7-10, 2023, P. 574-577, ISBN: 979-8-88896-530-6. URL: https://isg-konf.com/prospects-of-modern-science-and-education.

8. Polyvianchuk Andrii, **Zhang Le**. Analysis of the current state and development prospects of urban central heating in China. *Proceedings of the X International Scientific and Practical Conference «Modern methods of applying scientific theories»*, Lisbon, Portugal, March 14-17, 2023, P. 433-436, ISBN: 979-8-88896-520-7. URL: https://isg-konf.com/modern-methods-of-applying-scientific-theories.

9. Polyvianchuk Andrii, **Zhang Le**. Increasing the energy efficiency of buildings with household and centralized HVAC systems by using ground heat pumps. *Proceedings of the XXVI International Scientific and Practical Conference «Scientific trends and ways of solving modern problems»*, La Rochelle, France, July 04-07, 2023, P. 233-235, ISBN: 979-8-89074-572-9. URL: https://isg-konf.com/scientific-trends-and-ways-of-solving-modern-problems.

10. **Zhang Le**, Polyvianchuk Andrii. Influencing factors and energy-saving technology of heating boiler. *9th International Environmental Conference II: International Scientific and Practical Symposium on Decarbonization, Post-Mining and Energy Efficiency Infrastructure of Ukraine*, Vinnytsia: Vinnytsia National Technical University, September 25-27, 2024. P. 370-372, ISBN 978-617-8163-22-8. URL: https://press.vntu.edu.ua/index.php/vntu/catalog/book/854.

APPENDIX B

SUBSTANTIATION OF THE FEASIBILITY OF RATIONAL IMPLEMENTATION OF ENERGY-SAVING TECHNOLOGIES IN THE FIELD OF HEAT SUPPLY

With the acceleration of urbanization and people's increasing requirements for heating quality, the heating industry has an increasing demand for resources and energy. However, the energy utilization rate of traditional heat sources is not high enough, resulting in serious waste of resources and energy, and also seriously affecting the improvement of urban environment. Therefore, it is imperative to apply energy-saving and environmental protection measures and technologies to heating boilers, which is also an effective way to improve economic and social benefits.

Background and necessity of energy-saving technology. With the continuous growth of global energy demand and the intensification of climate change, energy conservation and emission reduction have become the focus of attention of governments and all sectors of society. Especially in the process of urbanization, building energy consumption accounts for a large proportion of total energy consumption, among which the energy consumption of heating and cooling systems is particularly prominent. According to the 2022 report of the International Energy Agency, the world is in a critical decade for creating a safer, sustainable and more affordable energy system. In order to achieve the global net zero emission target in 2050, it is expected that between 2020 and 2050, coal demand will drop by 90%, oil demand will drop by 75%, and natural gas demand will drop by 55%. The focus of the sustainable energy development strategy is to develop renewable energy sources (RES) and improve the efficiency of new technologies. In the EU, 43% of energy is consumed in the building sector, and 36% of greenhouse gases are emitted to the environment during energy production. Among them, urban development consumes the most energy, accounting for 43% of final energy consumption, and 65% of it is used for space heating and hot water supply [45]. To this end, the European Commission has developed a comprehensive strategy to achieve carbon-neutral buildings by 2050, such as the Green Deal [46]. Currently, the task of sustainable urban development is to upgrade buildings and their energy systems and introduce new technologies based on renewable energy to provide a reliable supply of heating and hot water to all regions.

Therefore, the rational implementation of energy-saving technical methods, especially in the heating sector, is not only the key to reducing energy consumption and carbon emissions, but also an important way to improve the ecological security of urbanized areas.

Factors affecting energy conservation and environmental protection of heating boilers.

(1) The exhaust volume and temperature of the boiler itself. In order to make heating boilers energy-saving and environmentally friendly, it is necessary to find the factors that affect the energy conservation and environmental protection effect of heating boilers. Starting from these factors, the heating boilers can be improved to make the heating boilers energy-saving and environmentally friendly. Among the factors that affect the energy conservation and environmental protection of heating boilers, the exhaust volume and temperature of the heating boilers are the most important. The temperature of the exhaust gas emitted by the heating boiler is very high, which contains a large amount of heat. It can also be regarded as containing a large amount of heat. Therefore, if the heating boiler continues to exhaust a large

amount of smoke, a considerable part of its own heat will be lost, which will greatly reduce the temperature of the heating boiler. A large amount of raw materials have to be consumed to raise the temperature back. It can be seen that this process increases the energy consumption of the heating boiler [47,48].

(2) Carbon content in boiler slag. The carbon content in the slag of the heating boiler is also an important factor in measuring the energy-saving and environmental protection effect of the heating boiler. If the staff wants to make the heating boiler work in an energy-saving and environmentally friendly way, they can choose to achieve this by reducing the carbon content in the slag of the heating boiler. Using some coal with a high moisture content as the raw material for the operation of the heating boiler will make the carbon content in the slag of the heating boiler too high. This is because the coal with a high moisture content often cannot be fully burned in the heating boiler, and there will be a considerable amount of residue, which not only greatly increases the carbon content in the slag of the heating boiler, but also increases the consumption of coal, because in order to make the heating boiler reach the target temperature, more coal must be consumed, which greatly reduces the energy-saving and environmental protection effect of the heating boiler. At the same time, the unreasonable setting of the working parameters of the heating boiler will also lead to an increase in the carbon content in the slag of the heating boiler. The preset working parameters of the heating boiler will have an impact on the operation of the heating boiler. If the working parameters are not set scientifically and reasonably, it is easy to cause some coal to be discharged out of the furnace before it is completely burned, resulting in a large amount of waste of coal and an increase in the carbon content in the slag of the heating boiler. Figure B.1 shows the coal slag that is not fully burned.

Fig. B.1 – Inadequately burned cinder

The main reason is that the fuel with a high moisture content is not fully burned in the boiler, and some of it will remain. This not only greatly increases the carbon content in the slag of the heating boiler, but also increases the fuel consumption, thus greatly reducing the energy-saving and environmental protection effect of the heating boiler [49].

In addition, if the boiler is not set with scientific and reasonable working parameters, the carbon content in the slag of the heating boiler will also increase. The operation of the heating boiler will be affected by the pre-set working parameters. Therefore, the working parameters of the heating boiler should be set as scientifically as possible, so that the slag can be discharged outside the furnace after the fuel is fully burned, reducing the carbon content in the slag of the heating boiler and avoiding the waste of fuel [50].

(3) Thermal efficiency of boilers. A heating boiler can be regarded as a device that converts energy, that is, it converts the energy stored in raw materials such as coal into heat. The standard for measuring the energy conversion effect of a heating boiler is thermal efficiency, which is also an important factor affecting the energy

conservation and environmental protection of a heating boiler [51]. By analyzing the thermal efficiency of a heating boiler, we can obtain the combustion conditions of the heating boiler for coal and the specific operating conditions, and intuitively understand the energy consumption of the heating boiler. If the staff does not operate the heating boiler in a standardized manner, the design of the heating boiler furnace is not reasonable and scientific, and the inspection and maintenance of the heating boiler is not carried out in a timely manner, the actual thermal efficiency of the heating boiler will be low, which will ultimately lead to high operating energy consumption of the heating boiler [52].

In the process of operation of heating boilers, more energy and resources will be consumed, which will have a certain impact on the environment. Therefore, it is necessary to analyze the factors affecting the energy saving of heating boilers from an objective perspective, and adopt effective energy-saving and environmental protection technologies to improve the operation mode of heating boilers, reduce the energy consumption of heating boilers, and promote the healthy and sustainable development of the heating industry [53].

Current status and development trend of energy-saving technology. In recent years, with the advancement of science and technology, energy-saving technology in the heating sector has made significant progress. The most direct way to reduce the energy consumption of heating and cooling in buildings is to reduce energy demand, for example through intelligent indoor temperature control systems [54], the use of double-layer facades [55] and optimization using building information models (BIM) [56]. In this process, conducting smart energy audits (which can also be facilitated by BIM data) is very useful and can significantly speed up the renovation of existing buildings. However, an analysis of the energy efficiency of buildings in different regions of the European Union published in references [57] showed that there are differences in heating/cooling demand and energy consumption in different climate zones, which makes it difficult to make universally applicable recommendations for all climate zones.

At the same time, existing heating systems need to be modernized to reduce energy consumption and achieve decarbonization. References [58] published a review on the use of modern technologies based on renewable energy in district heating. Studies have shown that the use of solar energy, geothermal energy, and heat pumps can improve the efficiency of district heating systems and reduce greenhouse gas emissions. The transition to the fourth generation district heating (4GDH) system characterized by the use of renewable energy will help better integrate the links between energy sectors, reduce network losses, and promote the integration of renewable energy [59]. The following are some of the main energy-saving technologies and their current application status:

(1) Intelligent temperature control system. The intelligent temperature control system can automatically adjust the operating status of heating and cooling equipment according to factors such as indoor and outdoor temperature and personnel activities through sensors and automatic control technology, thereby reducing energy waste. Studies have shown that intelligent temperature control systems can save 10%-30% of energy consumption. Figure B.2 is a simple intelligent temperature control system model. It reflects that a smart home heating system is mainly composed of intelligent temperature control equipment, mobile application control (mobile phone app), floor heating system, wireless sensors and other elements.

Fig. B.2 – Simple intelligent temperature control system model

Smart thermostats control the room temperature in your home or apartment, typically via an app on your smartphone, ensuring the perfect temperature for comfort and coziness. Smart thermostats provide full control of your home heating – whether it's radiators or floor heating – from anywhere, at any time. In the morning: before you even wake up, your smart heating solution automatically raises the room temperature, ensuring a pleasant start to the day. During the day: when you're not at home, smart heating lowers the room temperature to reduce energy consumption. At night: automatically lowers the temperature, saving even more energy. Smart thermostats not only ensure that the room temperature is at the right temperature at the right time, thus increasing comfort. They can also adjust the room temperature according to the user's schedule, saving up to 30% of energy.

(2) Double-layer facade technology. A double-skin facade is a building exterior wall design that reduces the amount of energy required for heating and cooling by

creating an air layer between the building exterior walls, reducing heat transfer. This technology has been widely used in office buildings and public buildings in Europe and other places, and can significantly improve the energy efficiency of buildings.

Although the concept of double-skin facades has been around for a long time, there is still a growing trend for architects and engineers to use them. In particular, in the design of skyscrapers, they like their transparent facades, excellent thermal and acoustic performance, reduced air conditioning costs, and the elimination of the need for special technical windows [60].

In addition, the double-skin facade can adapt to overly cold or overly hot weather. Its rich functionality makes it interesting: through small adjustments, such as turning on or off the intake or exhaust fans or activating the air circulation system, the function of the entire facade can be changed. Figure B.3 shows how the double-skin facade works.

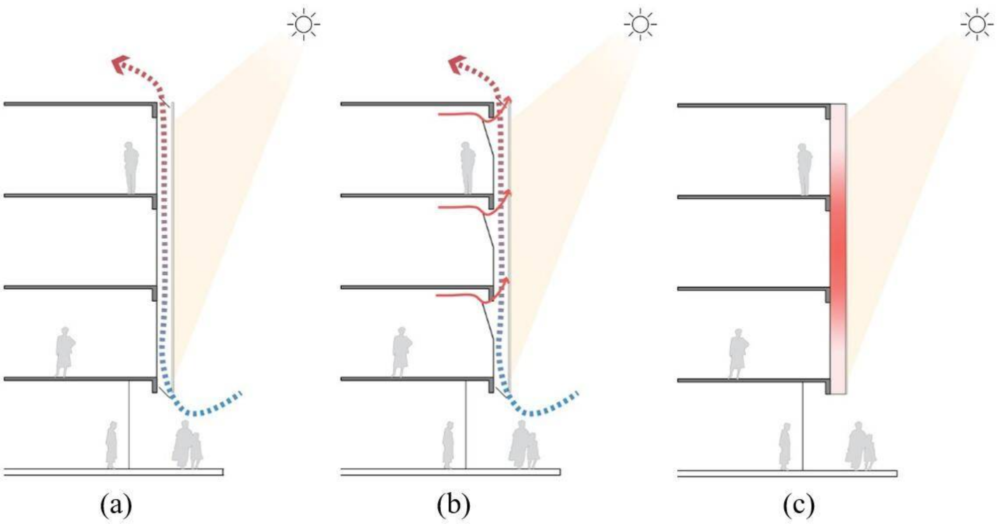

Fig. B.3 – Working principle of double-layer façade

Figure B.3 (a) shows that in hot climates, the air layer of a double facade can indeed reduce heat accumulation by exhausting hot air, thereby reducing cooling energy consumption. This process is usually achieved through natural ventilation or mechanical ventilation, ensuring that hot air can be effectively exhausted from the outside of the building. Figure B.3 (b) shows that excess heat energy is exhausted through the chimney effect, in which the uneven density of the air creates a circular movement that causes the hotter air to be exhausted. As the temperature in the air layer rises, it is exhausted, isolating it from the heat source and bringing some coolness to the environment. Figure B.3 (c) shows that in cold climates, the air layer of a double facade can act as an insulating layer to reduce heat loss. Solar radiation heats the air in the air layer, and this warm air can then be designed into the interior, reducing the reliance on heating systems. The role of air filters is to ensure that the air entering the interior is clean while retaining heat energy.

Overall, double facades are highly dependent on external conditions (solar radiation, external temperature, etc.) which directly affect the internal comfort and quality of life of the users. Therefore, meticulous design is crucial for every project, requiring in-depth knowledge of sun direction, environment, regional radiation, temperature conditions, building occupancy, etc.

(3) Building Information Model (BIM). BIM technology can accurately analyze and optimize the energy consumption of buildings through digital modeling. Through BIM technology, designers can simulate different energy-saving solutions and select the optimal energy system configuration during the building design and renovation process, thereby reducing the energy consumption of the building. Figure B.4 shows the role of BIM technology in improving building energy conservation.

The simulation performance analysis function of BIM technology can simulate the performance of buildings under different conditions, such as energy consumption,

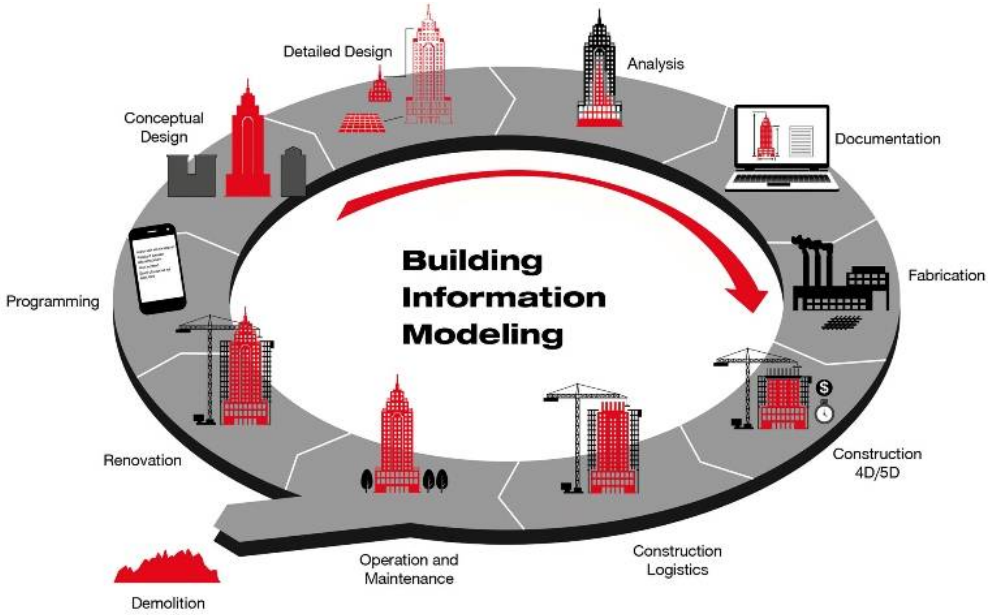

Fig. B.4 – Role Of Building Information Modeling Services In Making Buildings Energy Efficient

thermal comfort, lighting, sound insulation, etc. These analyses can help designers understand the performance of buildings more comprehensively, find problems and potential room for improvement. For example, in terms of energy consumption analysis, the design team can simulate the energy consumption of the building through BIM technology to find ways to reduce energy consumption, such as changing the orientation of the building, using more efficient materials, etc.

In terms of thermal comfort analysis, the design team can simulate the thermal comfort of the building through BIM technology and find ways to improve thermal comfort, such as changing the ventilation system of the building, using more efficient insulation materials, etc.

According to statistics, the use of BIM technology can reduce energy consumption by more than 10%. For example, in a large commercial complex project, the use of BIM technology for energy consumption analysis can find and solve the problem of peak energy consumption in the early stage of design, thereby reducing energy consumption to a minimum. At the same time, BIM technology can also analyze indoor lighting, ventilation and air quality, thereby optimizing the comfort and energy saving of the building and improving the green performance of the building. The application of BIM technology can not only achieve the goal of building energy conservation, but also improve design efficiency and accuracy, helping designers to develop more reasonable and scientific design plans [61].

In addition, the external wall enclosure structure plays a vital role in building energy conservation and has very important practical significance for energy-saving design work. Using BIM technology, taking the external structure as the starting point, in-depth exploration of building energy conservation is carried out. It is necessary to fully consider factors such as heat load and cold load and correctly analyze the actual situation of the indoor thermal environment [62]. This process covers the latent heat of indoor heat sources and the latent heat of indoor moisture sources, and must fully combine the heat loss of the enclosure structure and the heat loss caused by air circulation. If the heat obtained is a negative number, it means that heat dissipation has occurred. When the total amount of heat lost is greater than the total amount of heat obtained, the total amount of heat obtained inside the room is negative, so the amount of heat obtained and lost is a direct factor affecting the heat load of the entire room [63].

(4) Renewable energy heating system. The application of renewable energy such as solar energy and geothermal energy in heating systems has gradually become an important means to reduce dependence on fossil energy and reduce carbon emissions. Especially in regional heating systems, the integration of renewable energy can significantly improve the energy utilization efficiency of the system.

Traditional heating systems use combined heat and power (CHP) and gas boilers to consume gas to generate heat for space heating of buildings. The use of gas can cause a large amount of CO_2 emissions. In order to reduce greenhouse gas emissions, one solution is to use electrically driven heat pumps to heat buildings. However, this will increase the cost in electricity and have an impact on the electricity grid, especially in winter when the heat demand is relatively high. This can lead to extra load to the power grid and affect its stability. To solve this problem, the usage of local renewable resources is considered as a substitute [64]. Renewable resources mainly include wind energy, solar energy and geothermal energy, which all depend on weather conditions. Thus, the heating system requires battery storage systems and thermal energy storage to compensate the imbalance between generation and demand for electrical energy and thermal energy, respectively. The district heating network of the traditional heating system and the proposed renewable heating system (RHS) is shown in Figure B.5.

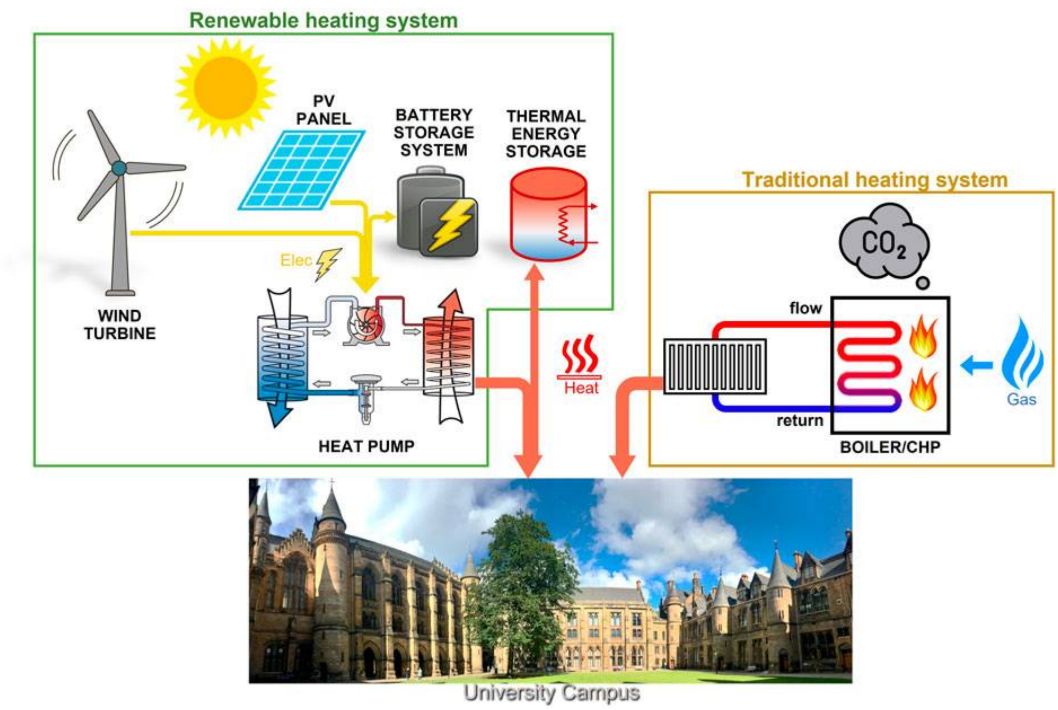

Fig. B.5 – Heating system of university campus（The University of Glasgow）

Economic and Feasibility Analysis of Energy-Saving Technology. Although energy-saving technology has significant advantages in reducing energy consumption and reducing carbon emissions, its economy and feasibility are still issues that need to be considered during implementation. The following is an analysis of the economy and feasibility of energy-saving technology:

(1) Initial investment cost and operation and maintenance cost. Many energy-saving technologies (such as intelligent temperature control systems, double-layer facades, BIM technology, etc.) require higher investment costs in the initial implementation. For example, smart temperature control systems are expensive to install and commission, and the construction cost of double-skin facades is significantly higher than that of traditional building facades. However, the long-term energy-saving effects of these technologies can significantly reduce the operating costs of buildings, and the initial investment can usually be recovered within a few years. The operation and maintenance costs of energy-saving technologies are relatively low. For example, smart temperature control systems reduce the need for manual intervention and reduce operation and maintenance costs through automated control. In addition, the operating costs of renewable energy heating systems are also lower than those of traditional fossil energy systems.

(2) Modernization of home heating systems. One of the main criteria for effectively modernizing home heating systems is its economic evaluation and available funds. There are relatively few studies on determining the optimal investment for modernization, and relevant research is still ongoing. Recent studies have shown the importance of incorporating the entire time horizon of the building life cycle in optimization [65], which provides a more realistic approach to building decarbonization,

reflects the fact that investment decisions can be made at multiple stages of the building life cycle, and takes into account the value of investment flexibility. Reference [66] proposes a method to determine the optimal decarbonization strategy for an existing district, which takes into account investment decisions for building-level energy supply and the modernization and expansion of existing district heating systems. The simulation uses two existing study areas in the city of Chur, Switzerland, which include residential and mixed-use development projects. The results show that modernization is the main cost driver for any decarbonization strategy. Therefore, the choice of technology and the size of the energy system itself can have a better impact on emission reduction at a moderate increase in cost. In addition, the study shows that the combination of heat pumps, hot water storage tanks and solar photovoltaic systems is not only the most CO_2-optimal, but also the most cost-optimal for buildings without district heating.

(3) Policy support and financial subsidies. Many countries and regions encourage the application of energy-saving technologies through policy support and financial subsidies. For example, the EU has provided a lot of financial support for energy-saving renovation of buildings through the "Green Deal" and "Renovation Wave" programs. These policies not only reduce the implementation cost of energy-saving technologies, but also improve their economy and feasibility.

(4) Adaptability to climate regions. There are significant differences in heating and cooling needs in different climate regions, so the application of energy-saving technologies needs to be adjusted according to specific climate conditions. For example, in cold regions, the energy-saving effect of double-layer facades and intelligent temperature control systems is more significant, while in warm regions, the application of solar heating systems is more advantageous.

Reasonable introduction of new energy heating technology. New energy heating has many advantages, such as less pollution, low energy consumption and stable heating. In order to reasonably implement energy-saving technology, various regions in China have increased the research and development and use of new energy heating. The main new energy heating methods are as follows.

(1) Air source heat pump. Air source heat pump uses the energy in the air as the main power, drives the compressor to operate through a small amount of electricity to achieve energy transfer, and does not require complex configuration, expensive water intake, recharging or soil heat exchange system and dedicated machine room. It can gradually reduce the large amount of pollutant emissions caused by traditional heating to the atmospheric environment, ensure heating efficiency and achieve energy conservation and environmental protection.

(2) Carbon crystal plate. Carbon crystal plate is a new type of low-temperature radiant heating system developed with carbon crystal heating plate as the core component. It has the advantages of high comfort, long service life, high thermal efficiency, uniform heat dissipation, and fast heating.

(3) Gas wall-mounted boiler, gas boiler. Gas wall-mounted boiler has a powerful family central heating function, which can meet the heating needs of multiple rooms. Each room can set a comfortable temperature according to needs, and can also decide to turn off the heating of a room separately according to needs. It can also provide a large flow of constant temperature sanitary hot water for family bathing, kitchen and other places. Gas boilers can be used for central heating in areas with a relatively concentrated population in towns and communities with gas pipelines.

(4) Ground source heat pump. Ground source heat pump includes water source heat pump, soil source heat pump, etc. It uses the natural characteristics of groundwater or surface water and soil temperature being higher than atmospheric temperature in winter and lower than atmospheric temperature in summer. By inputting a small amount of high-grade energy (such as electricity), it realizes the transfer of low-grade heat energy to high-grade heat energy. This heating technology also has low energy consumption, no pollution, zero emissions, and abundant resources, which are inexhaustible. Water source heat pump should be close to the water source, and it is not suitable for long-distance heat transmission. In addition, the problems such as difficulty in recharging and waste of water resources in the application process have become a bottleneck for the application of this technology. Soil source heat pump generally refers to the utilization of shallow geothermal energy about 200m underground with a constant temperature of 10°C-25°C. Its cleanliness and renewability make it a very good alternative energy source.

(5) Sewage source heat pump. Sewage source heat pump is an innovative technology that mainly uses urban sewage as a cold and heat source for energy extraction and storage. It consumes a small amount of electric energy with the help of the physical circulation change of refrigerant inside the heat pump unit system, so as to achieve the effect of refrigeration and heating. Urban sewage is composed of industrial wastewater and domestic sewage, with a huge amount of water, which is a kind of renewable heat energy resource containing rich low heat energy. Sewage source heat pump air conditioning system takes urban sewage as the cold and heat source of buildings, which is an important technology to solve the winter heating, summer air conditioning and annual hot water supply of buildings, and is also an idea and effective way to the development and utilization of urban sewage resources. At the same time,

urban waste heat and CO_2, SO_2, NO_X, dust and other pollutants emissions are reduced. Compared with other heat sources, the technical key and difficulty of sewage source heat pump lies in anti-blocking, anti-pollution and anti-corrosion.

(6) Solar energy. Solar energy is renewable energy, and its value is increasing because of its cleanliness. China is rich in solar energy resources, most notably Lhasa on the Tibetan Plateau. However, in areas where solar energy is insufficient, electric auxiliary heating can be used, and in areas where residents are more dispersed, this method can be used for heating. But solar heating is vulnerable to weather and climate, and the initial investment is high, so the development is restricted.

(7) Regenerative electric heating system. Regenerative heaters are designed to generate electricity and heat in 6-8 hours at night (from 23:00 to 7:00 the next day) by using low-price electric energy during the off-peak period of the power grid. Energy conversion and storage, in the peak hours of the power grid, in the way of radiation, convection will be stored heat out, to achieve 24 hours a day indoor heating. That is to say, only 6-8 hours of electricity a day, can achieve 24 hours of heating, to achieve the purpose of saving heating costs.

Table B.1 compares the advantages, disadvantages and economic efficiency of commonly used new energy heating methods.

The rational implementation of energy-saving technologies and methods is significantly feasible and necessary in the field of heating. Through the application of energy-saving technologies such as intelligent temperature control systems, double-layer facades, BIM technology and new energy, it is possible to effectively reduce the energy consumption and carbon emissions of buildings and improve the ecological security of urbanized areas.

Table B.1 – Advantages, disadvantages and economic comparison of common new energy heating methods

Serial number	Heating mode	Working principle	Advantage	Shortcoming	Initial investment ($RMB/10m^2$)	Operating costs ($RMB/10m^2$)
1	Air source heat pump	Air source heat pump	Heating time and temperature can be set freely	Large initial investment, large power consumption, poor comfort	10000	21
2	Wall mounted gas boiler	Household installation of wall-hung boiler	Self-defined heating time, free opening, independent temperature regulation, can simultaneously solve the heating and domestic hot water demand	Heating furnace life of 15 years, antifreeze	6000 (equipment 4000 indoor facilities 2000)	28
3	Carbon crystal plate	Pure carbon particles heat, power that is heating	Easy installation, small initial investment	High operating costs	3000	62
4	Geothermal heat pump / water source heat pump	Buried tube geothermal heat pump	High energy efficiency and low operating costs	Limited by geographical conditions, high initial investment, groundwater recharge	21000	18
5	Sewage source heat pump	Sewage source heat pump compressor system	Relatively low initial investment and low operating costs	Pipe blockage	18000	17
6	Solar-assisted electric heating	Solar heating, electric auxiliary heating in the absence of solar	Simultaneously solve the heating and domestic hot water demand	Larger initial investment	10000	16
7	Regenerative electric heater	Convert electrical energy into heat	Easy installation, small initial investment, the use of peak and valley electricity prices	High operating costs	7000	28

Although energy-saving technologies require higher investment costs in the initial stage of implementation, their long-term economic and environmental benefits are significant. Through policy support, technological innovation and public participation, the widespread application of energy-saving technologies will provide important support for sustainable development in the process of urbanization.

APPENDIX C

ACTS OF IMPLEMENTING THE RESULTS OF THE DISSERTATION WORK

«APPROVE»
Vice-Rector for Scientific and Pedagogical Work and Organization of the Educational Process of Vinnytsia National Technical University
«14» January 2025
Oleksandr PETROV

ACT

of introduction into the educational process of the results of Zhang Le's dissertation work
«Improving the ecological security of urbanized areas through the rational introduction of energy efficient and environmental technologies in the field of heat supply»

We, the undersigned: Head of the Department of Ecology, Chemistry and Environmental Protection Technologies (ECEPT), Prof. Ishchenko V.A., Head of the Section of Ecology and Environmental Protection Technologies of the ECEPT Department, Ph.D., Prof. Petruk R.V. and Assoc. Prof. Vasylkivskyi I.V. have drawn up this act stating that the results of dissertation research by a postgraduate student of the ECEPT Department, Zhang Le, have been introduced into the educational process and scientific work of VNTU, namely:

– results of systematization and analysis of energy-efficient and environmental technologies in the field of heat supply;

– recommendations for reducing environmental pollution by harmful emissions from boiler houses, increasing the rational use of energy and fuel resources in the field of municipal energy.

The indicated results of Zhang Le's scientific and practical research were used in the training of bachelors and masters in specialties 183 - "Environmental Protection Technologies" and 101 - "Ecology" in lecture and practical classes in the disciplines "Technoecology", "Industrial Ecology", "Atmospheric Air Protection Technologies" and "Ensuring Environmental Safety".

The result of introducing the materials of Zhang Le's dissertation into the educational process at the ECEPT Department is an increase in the efficiency of training qualified specialists in environmental protection technologies and ecology.

«10» 01 2025

Ishchenko V.A.
Petruk R.V.
Vasylkivskyi I.V.

ІНТЕР·ЕКО

ПРОМИСЛОВА ЕКОЛОГІЯ ТА ЗАХИСТ ДОВКІЛЛЯ

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№25_04 від 15.01.2025 р.

«APPROVE»
Director of PE "Inter-Eco"
__________ Vadym HONCHARUK
«15» January 2025

ACT
implementation of the Zhang Le's dissertation work results
«Improving the ecological security of urbanized areas through the rational introduction of energy efficient and environmental technologies in the field of heat supply»

Members of the commission include: director V.S. Honcharuk, leading engineer V.V. Chyzhyk, and engineer D.Yu. Yermakov made this act stating that the results of Zhang Le's dissertation work, prepared under the specialty 183 - Technologies of environmental protection, were implemented in the scientific and production activities of PE "Inter-Eco".

The Commission notes that certain results of Zhang Le's dissertation are used by INTER-ECO Private Enterprise for:

– assessing the effectiveness of greening and decarbonization of urban areas based on the method of rational implementation of energy-saving technologies while ensuring maximum environmental and economic effect;

– conducting scientific and applied research into the effectiveness of implementing innovative energy-efficient and environmental technologies at social infrastructure facilities.

Signatures of commission members: Vadym HONCHARUK
Victoria CHIZHYK
Denis YERMAKOV