Heliyon 9 (2023) e16732

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Post-evaluation analysis on urban coal, oil and gas resources comprehensive utilization governance project: A case study in Fuxian, China

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ARTICLE INFO

Keywords:
Double carbon
Urban governance
Emergy-based energy return on investment
Energy efficiency
Cost-benefit analysis
Emergy intensity

ABSTRACT

China's energy and chemical enterprises in the resource-based urban cities face challenges of climate change targets. Coal, Oil and Gas Resources Comprehensive Utilization (COGRCU) project can address the carbon and hydrogen imbalance between conventional methanol from coal and natural gas. Moreover, it can improve energy conversion rates and carbon resource recovery. Therefore, it is a better way for energy and chemical enterprises to transition to sustainable development and advocated by enterprises in resource-based cities. In practice, the actual benefits of the COGRCU project are often different from those expected from prior assessments, and the main factors contributing to the differences need to be identified. Therefore, it is necessary to propose a post-evaluation methodology for the COGRCU project to assist energy and chemical enterprises in identifying these constraints and optimize project management. This study considers energy and monetary flows, combines emergy-based energy return on investment (EmEROI) and cost-benefit analysis (CBA), and proposes a post-evaluation methodology of the COGRCU project based on the case study of YC Group's Fuxian COGRCU project in Fuxian County. In addition, the emergy per unit money, emergy per unit labor, and bio-resources emergy per unit area of Yan'an City are measured. Results showed that indirect energy and labor input emergy are the primary contributors to improving the projects' energy efficiency. Operating costs reduction are the key factors for improving economic benefits. The indirect energy has the highest impact on the project's EmEROI, followed by labor, direct energy, and environmental governance. Several policy recommendations are raised, including strengthening policy support, such as advancing the formulation and revision of fiscal and tax policies, improving project assets and human resource management, and increasing environmental governance efforts.

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https://doi.org/10.1016/j.heliyon.2023.e16732
Received 2 January 2023; Received in revised form 21 May 2023; Accepted 25 May 2023
Available online 29 May 2023

1. Introduction

In September 2020, the Chinese government stated its climate change targets: peaking carbon dioxide emissions in 2030 and achieving carbon neutrality in 2060 [1]. In other words, it will take less than ten years for China to reach its carbon peak and less than 40 years to reach carbon neutrality, which is about half the time it takes for developed countries. Efforts and speed of emission reduction are unprecedented and daunting. However, compared to Europe and the United States, China's CO_2 emissions increased from 8.15 billion tons in 2010 to 9.90 billion tons in 2020 [2], continuously growing at an average annual rate of 2%. Gross domestic product (GDP) is just over 10,000 US dollars. Industrialization and urbanization are ongoing. Energy consumption [3] will keep increasing. Most of the total carbon emissions are attributable to energy-related carbon emissions [4]. Therefore, energy enterprises must integrate the 'double carbon' target into their medium- and long-term development strategies and actively deploy green, low-carbon industries, such as wind power and photovoltaic (PV) [5]. However, the dependence of renewables on technological advances to replace fossil energy makes the energy transition costly and long lasting. The energy sector needs to promote carbon emission reduction using three methods urgently: (1) energy conservation and emissions reduction, (2) energy substitution and emissions reduction (replacing traditional fossil energy fuels with renewable energy) [6] and (3) de-energy emissions reduction (closures and transfers and other means of de-productivity) [4,7,8]. Among these methods, energy conservation and emissions reduction refer to all technically feasible, economically reasonable, environmentally and socially acceptable measures to improve energy efficiency. It is easier than energy substitution emissions reduction and has greater potential than de-energy emissions reduction. Its improvements can account for more than 60% of the emission reductions before carbon dioxide emissions peak [9]. Therefore, reducing carbon emissions by improving energy efficiency has great potential.

Shaanxi is a resource-based province, China's third-highest coal and the highest oil and gas producer [10]. Energy and chemical industries with high pollution and emissions account for half of Shaanxi's total industrial output value. This province has eight resource-based urban cities: Yan'an, Yulin, Tongchuan, Weinan, Xianyang, Baoji, Luonan, and lueyang. They rely heavily on fossil energy consumption to achieve rapid economic growth, which contradicts the economic and social development required to achieve the 'double carbon' target. The COGRCU project focuses on petrochemical, natural gas and coal chemical industries and addresses issues regarding carbon and hydrogen imbalance, such as the coal chemical industry with more carbon and less hydrogen and the natural gas chemistry industry with higher hydrogen and lower carbon. In addition, the project improves the total utilization rate of carbon resources and energy efficiency. Therefore, under the background of 'double carbon', the COGRCU project is essential in transforming and upgrading energy and chemical enterprises, particularly in resource-based urban cities in Shaanxi Province. However, even though energy efficiency reflects project benefits to some extent, it is presented as energy flows rather than as a recognized criterion by which enterprises can measure project benefits. Energy and chemical enterprises emphasize the economic benefits output per unit of money input [11]. In addition, the COGRCU projects have undergone detailed feasibility analyses before their implementation and have achieved several economic benefits in the formal operations. However, there is a difference between the actual and expected results of the project, which is difficult to distinguish. Therefore, conducting a post-evaluation of the projects and considering both energy and monetary flows are necessary for identifying the differences.

Increasingly, researchers are focusing on reducing energy consumption by improving energy efficiency to maintain or promote sustainable economic, social, and environmental development. Energy return on investment (EROI) refers to the energy available to modern society after extraction, processing and delivery [12,13]. It is the most appropriate method for measuring net energy [14], which is the ratio of energy output to energy input [12]. Hence, energy efficiency can be measured by EROI. It can calculate energy inputs by considering environmental energy costs, such as direct and indirect damage to social and natural resources [15]. However, in empirical research, the lack of conversion factors often makes it challenging to measure the EROI value by adjusting input and output variables for the same unit. Thus, an emergy - based method will be used instead. The emergy theory assumes that different energies of equal calorific value contain different amounts of implied energy, such as 1 J of coal and 1 J of natural gas. It is more reasonable than the calorific value. EmEROI uses the emergy modified calorific value method in converting energy output and input in a traditional EROI into solar emergy and then calculates the ratio, which better reflects the actual value and contribution of energy [16].

EROI shows different results even for the same energy data because of differences in the choice of research boundaries, energy intensity, whether to correct energy quality, differences in extraction technology, and geographic regions [13]. To address this issue, in terms of the analytical framework, Mulder et al. [17] proposed a unified analytical framework for EROI. Murphy et al. [18] used a two-dimensional framework of input hierarchies and output boundaries to determine standard EROI analytical boundaries to compare different EROI values, effectively addressing the above issues. In terms of selecting the conversion factors, while EROI can consider environmental impacts [19], most studies still calculate a standard EROI by considering only direct and indirect energy inputs [13,17,20,21]. These inputs are typically converted to thermal equivalent [22,23] or solar emergy [16], or exergy equivalent [24,25,26]. However, the latter two are not widely used due to data source limitations. The thermal equivalent assumes that 1 J of oil, coal, and electricity has the same quality [19]. It is obviously unreasonable. Scholars generally correct it based on a quality factor. For instance, they typically use the method of fuel output and price-adjusted relative price proposed by Berndt [27,28] for correction but with limited effect. Instead, EmEROI is more appropriate than the EROI-Divisia index when evaluating energy extraction projects [16]. At the analytical level, scholars focus on measuring or projecting the EROI values for energy production at the macro level. For example, some scholars measured or predicted EROI values of fossil energy extraction in Canada, the United States, Norway, Pakistan and China [29,30,31,32,33,34,35]. They set fossi energy extraction as the output boundary, and the input hierarchy only considers direct and indirect energy inputs. The continuous depletion of fossil energy has led experts to focus on the EROI of renewable energy generation and use EROI values to determine if this energy can substitute fossil energy [21,36]. In terms of accelerating the global transition to a green, low-carbon energy system, some experts have simulated and measured the EROI of the energy system under various scenarios.

For example, Hall et al. [20] used the EROI approach to evaluate the minimum EROI obtained from energy development to achieve sustainable economic activities and social functions, which suggests that any given organism or system must comply with the 'law of minimum EROI'. Capellán-pérez et al. [37] used the EROI method to assess the energy and materials investments required to transition from fossil to renewable energy in the global power sector. Delannoy et al. [38] examined the energy necessary for the production of oil liquids and question the feasibility of a global and fast low-carbon energy transition. However, only a few experts have measured the EROI at the regional level, such as Huang et al. [39]. The majority of these studies are multi-input, single-output production projects. When studying a multi-input, multi-output production project, such as a coal-to-oil project or the COGRCU project, for example, Kong et al. [23] used EROI to measure the various values of the standard EROI of China's Shenhua coal-to-oil project. The $EROI_{stnd}$ values were significantly lower when CCS technology inputs were considered. However, the Shenhua coal-to-oil project generated four main products and four by-products. The Fuxian COGRCU project generated eighteen products and by-products. EROI can not be measured because most products do not have a corresponding average low calorific value. To solve this problem, Chen et al. [16] incorporated the emergy theory and method [40] into EROI calculations and used the research results of Liu et al. [41] to deal with this problem effectively. In recent years, experts have mostly adopted the EROI method in combination with multi-objective decision-making methods and Slack Based Measure-Data Envelopment Analysis (SBM-DEA) to evaluate the sustainability of various systems or production processes [42,43,44,45]. Few experts have combined emergy methods with EROI to examine energy production activities. Only Chen et al. [16] combined emergy analysis with EROI to measure the EmEROI of the Daqing Oil Field. In this respect, estimates of the EmEROI of the COGRCU project will enrich the research to a certain extent.

CBA is often used to assess the economic viability of energy systems and investments in the transition of existing energy systems [46] and determine whether initiating or continuing a project makes good economic sense [47]. It is also used to evaluate whether a project should be accepted from a cost-benefit perspective or combined with a positive shadow profit to identify which projects improve welfare [48]. For example, Annals et al. [49] used CBA to examine the economic feasibility of a high-speed rail project introduced in Spain in 1987. Djukic et al. [50] assessed the economic viability of an infrastructure investment project in Serbia that required tertiary wastewater treatment using CBA. Morimoto et al. [51] used CBA to examine the hydro-power projects in Sri Lanka and evaluate the Three Gorges Dam project under construction in China [52]. Therefore, We can use CBA to examine the economic feasibility of the COGRCU projects from a monetary flows.

To summarize, experts have extensively reviewed EROI, CBA, and their applications. However, existing research has focused on evaluating macro-production activities' energy efficiency or the economic benefit [30,51]. Only a few studies have assessed the energy efficiency and economic benefit of an energy and chemical project at the regional level from both energy and monetary flows. Meanwhile, several studies have extended the input hierarchy of energy production activities to the environmental governance

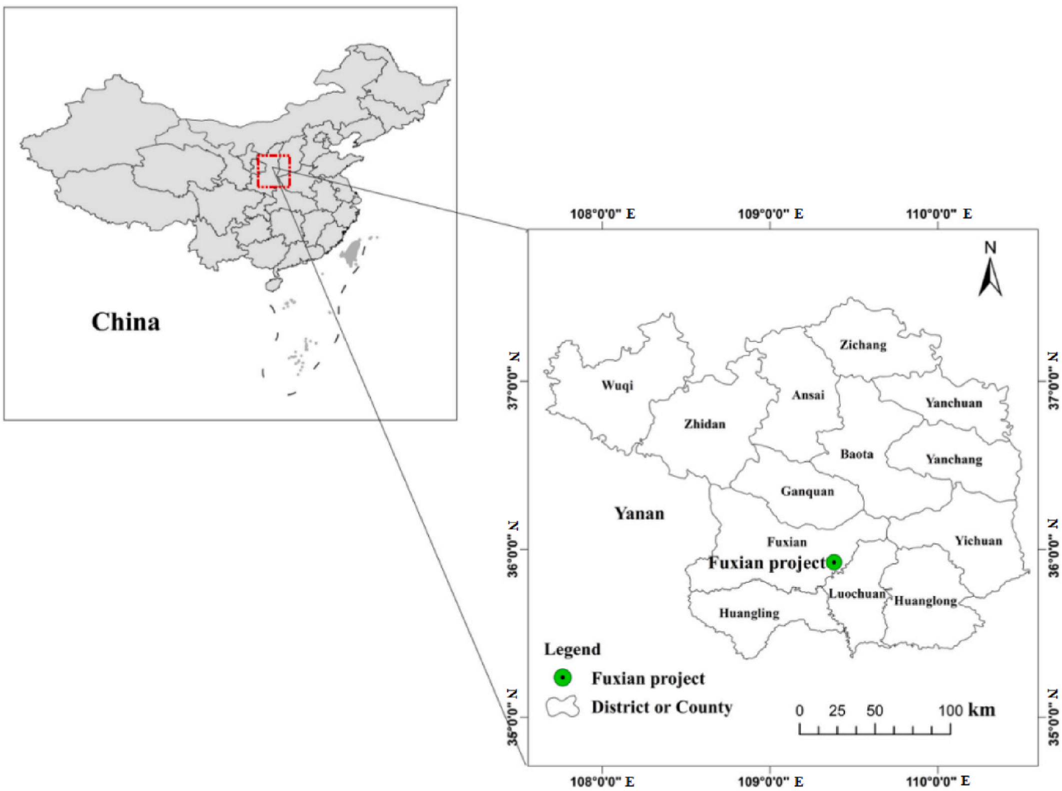

Fig. 1. Location of the Fuxian COGRCU project.

hierarchy proposed by Murphy et al. [19]. However, only a few studies on the EmEROI of the COGRCU project focus on direct energy, indirect energy, labor, environmental governance [23,36]. In addition, in terms of measuring or predicting the EROI of fossil energy production, most studies have converted input and output energy into thermal equivalent. Only a few studies converted it into solar emergy. Moreover, the emergy intensities are often replaced by other parameters, which affects the accuracy of the study.

Therefore, we considers energy and monetary flows, combines EmEROI with CBA and proposes a post-evaluation methodology of the COGRCU project based on the case study of YC Group's Fuxian COGRCU project. Values of the standard EmEROI, EmEROI with labor inputs added to values of the standard EmEROI, EmEROI with labor and environmental governance inputs added to values of the standard EmEROI, net energy, benefit-to-cost ratio and net benefits of the project as well as the emergy per unit money, emergy per unit labor and bio-resources emergy per unit area of Yan'an City are measured. The purpose of this study is to propose a post-evaluation methodology for the COGRCU project to identify the critical constraints that prevent energy chemical enterprises from fully realizing energy efficiency and economic benefits improvement through a case study of YC Group's Fuxian project and simultaneously help YC Group optimize project management. It can also promote transition development of these resource-based cities and urban governance, as well as help the local government formulate more appropriate policies to effectively mitigate the overall carbon emissions of the energy and chemical industry.

It is expected that this paper can make several contributions: first, the post-evaluation method we proposed can give consideration to the nature and economic attributes of COGRCU project, by calculating energy flow and monetary flow. Second, the emergy intensities calculation method for resource-based city is proposed. Based on the emergy theory and method, the emergy per unit money, emergy per unit labor, and bio-resources emergy per unit area of Yan'an City are measured. Finally, the combines EmEROI and CBA give a light for the COGRCU project sustainable development by post-evaluation, which balanced considering the energy efficiency and economic benefits of the project.

2. Methods and data

2.1. Fuxian COGRCU project

As shown in Fig. 1, the Fuxian COGRCU project is located in Fuxian, Yan'an City, Shaanxi Province, China. Its construction was completed in 2019 and officially launched into commercial operation in July 2020, with a total investment of 3222.48 million US dollars and a net profit of 65.95 million US dollars in 2021.

The Fuxian COGRCU project mainly uses oilfield-associated gas, naphtha and coal as feedstock to produce eighteen main products and by-products, such as polyethylene, polypropylene, 1-butanol, isobutyl alcohol, 2-propyl-1-heptanol, ethylene propylene rubber, stabilized light hydrocarbon, methyl tertiary-butyl ether, paraffin, ammonium sulfate, sulfur, fly ash, propane, C4 fractions, coal-based mixed pentene and propylene. Fig. 2 illustrates the main process flow. The project takes full advantage of YC Group's resource advantages. Compared with the same scale of methanol from coal, the total utilization rate of carbon resources increased by 26% and CO_2 emissions decreased by 3.70 million tons/year. Compared with the same scale of coal to olefin, the energy conversion rate increased by 21%.

2.2. Post-evaluation method of COGRCU projects

2.2.1. EmEROI model for COGRCU projects

The earth gets its energy from the sun, called solar energy and is often used as a basis for measuring the emergy of various kinds of energy. The direct and indirect consumption of solar energy required to create resources, products or services refers to the emergy of

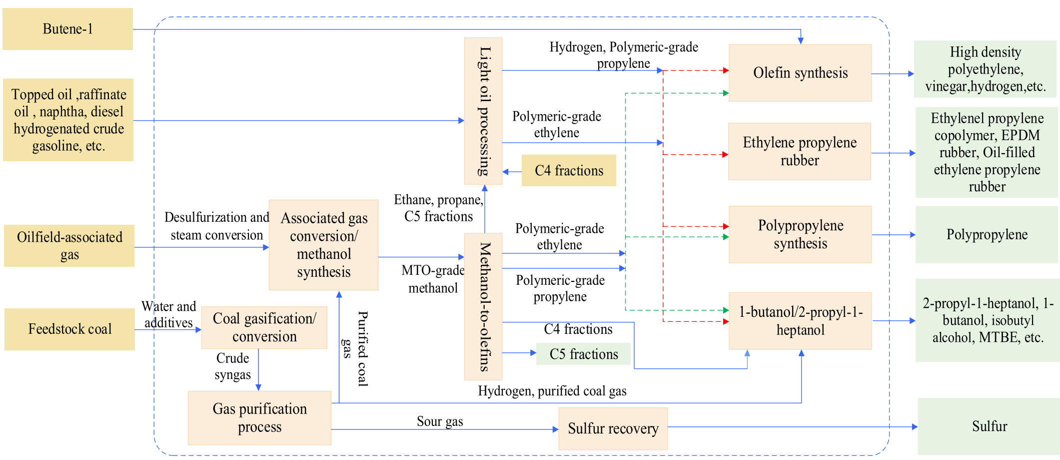

Fig. 2. Main process flows of the Fuxian COGRCU project.

solar energy measured in solar emjoules (sej) [53]. The weight assigned to different types of energy reflects the actual value and contribution of energy, which is consistent with the theoretical basis of the EROI model [16]. Therefore, the basic formula for calculating EROI [22] also applies to EmEROI (see Equation (1)).

$$EROI = \frac{Energy\ gained}{Energy\ required\ to\ get\ that\ energy} \tag{1}$$

EROI can be expressed in 100:1, where a given production process produces 100 J of output with 1 J of input [20]. Formula 2 is commonly used in practical calculation.

$$EROI = \frac{\sum_{i=1}^{n} E_i^{output}}{\sum_{i=1}^{n} E_i^{input}} \tag{2}$$

Where E_i^{output} and E_i^{input} are the thermal equivalent values of the total output and input of the ith energy, respectively, which implies that different energies of equal heat equivalents have the same working capacity, which is inconsistent with reality and is usually corrected with a quality factor [16] (see Equation (3)).

$$EROI = \frac{\sum_{i=1}^{n} \lambda_i E_i^{output}}{\sum_{i=1}^{n} \lambda_i E_i^{input}} \tag{3}$$

Where λ_i is the quality factor of the ith energy, calculated in detail in the literature [27,28], Formula 4 calculates the net energy [18].

$$\begin{aligned} &Net\ energy = Gross\ energy\ produced - energy\ invested\ to\ get\ that\ energy \\ &= Gross\ energy\ produced \times \left(1 - \frac{1}{EROI}\right) \end{aligned} \tag{4}$$

Formula 5 calculates the EmEROI of the COGRCU project based on Equations (1)–(4), combined with the actual COGRCU project.

$$\begin{aligned} EmEROI &= \frac{Em^{output}}{Emd + Emid + Em_{lab} + Em_{env}} \\ &= \frac{\sum_{q=1}^{n} Em_q^{output}}{\sum_{i=1}^{n} Emd_i^{input} + \sum_{j=1}^{m} Emid_j^{input} + Em_{lab} + Em_{env}} \\ &= \frac{\sum_{q=1}^{n} E_q^{output} P_q EMR}{\sum_{i=1}^{n} Emd_i^{input} + \sum_{j=1}^{m} Emid_j^{input} + Em_{lab} + Em_{ap} + Em_{wp} + Em_{disab} + Em_{eco}} \end{aligned} \tag{5}$$

Where Em^{output} is the total emergy of energy chemicals of the COGRCU project; Em_q^{output} the emergy of the qth energy chemicals; E_q^{output} the production of the qth energy chemicals; P_q the selling price for the qth energy chemicals; *EMR* the emergy per unit money; *Emd* the emergy of direct energy input; Emd_i the emergy consumed by the ith direct energy input; *Emid* the emergy of indirect energy input; $Emid_j^{input}$ the emergy consumed by the jth indirect energy input; Em_{lab} the emergy of labor input; Em_{env} the emergy consumed by environmental governance inputs; Em_{ap} the emergy of wind needed to dilute atmospheric pollution, in particular, by wind, which dilutes PM, CO_2, NO_x and SO_2 to background concentrations; Em_{wp} the emergy required for water pollutants to be diluted and broken down, in particular, the emergy of water required for water pollution to be diluted to background concentrations by rivers; Em_{disab} the emergy of human disability caused by atmospheric pollution, in particular, the loss emergy of human health due to emissions of PM, CO_2, NO_x and SO_2 and Em_{eco} the emergy of the loss of local ecological resources due to the acidification effect of NO_x and SO_2, in particular, the impacts on agriculture, forestry and fisheries.

Suppose the EmEROI of the COGRCU project is greater than 1:1. In terms of energy flow, this production activity can provide net energy for economic and social development. The higher the EmEROI value, the more the energy production process offers net energy for society. Per unit of energy can create more value. If EmEROI≤1:1, it is self-sufficient production or cannot provide net energy for economic and social development. The project requires much energy to sustain and this production is unsustainable in terms of energy flow.

2.2.2. System boundaries demarcation

Various selections of system boundaries will significantly influence the calculation results of Equations (1)–(5). The two-dimensional calculation standards established by Murphy et al. [19] are widely accepted in the literature, as detailed in Table 1, where the first subscript of the EROI identifier is the output boundary and the second subscript is the input hierarchy. $EROI_{stnd}$ is the standard EROI. According to Murphy et al. [19], the output boundary of the COGRCU project is an end-use stage, the input hierarchy is d + id + lab + env and ancillary services are temporarily excluded due to data limitations.

2.2.3. Emergy intensities

Emergy intensities are the solar emergy per unit energy or other units, which is used to convert the input and output variables of the COGRCU project into solar emergy to measure the EmEROI of the project further.

The emergy per unit money, emergy per unit labor and bio-resource emergy per unit area is the basis for measuring the EmEROI of the COGRCU project. Chen et al. [16] used industrial energy intensity to convert indirect energy inputs into joules when calculating the EmEROI of the Daqing Oil Field. The emergy intensity was derived from literature and the emergy per unit labor was replaced with the neighboring city of Harbin in 2004, which would affect the calculation results to a certain extent. Mu et al. [54] calculated the total emergy of agroecosystems in Yan'an City in 2006. Suppose we used these data as an approximate substitute for the total emergy of Yan'an City from 2019 to 2021, which will affect the accuracy of the calculation. This study does not directly refer to previous studies' estimate of the emergy intensity but, instead, calculates the emergy per unit money and emergy per unit labor based on the renewable resources, non-renewable resources and input and output emergy data of Yan'an City from 2019 to 2021 (see Equations (6)–(8)).

$$U = R + N + I + O \tag{6}$$

$$EMR = U/GDP \tag{7}$$

$$\tau_h = U/person \tag{8}$$

Where U is the total emergy of Yan'an City and R is the renewable resource emergy, including the emergy of renewable environmental resources and renewable natural resource products. The renewable environmental resources emergy includes solar emergy, wind emergy, rainwater potential emergy, chemical emergy of rainwater and rotational emergy of the earth. The renewable natural resource products emergy includes emergy for grains, tubers, oil seeds, vegetables, fruits, meat, eggs, dairy, cashmere, etc. N is the non-renewable resources emergy, including non-renewable natural resources and non-renewable energy products. The non-renewable natural resources emergy includes the net loss of topsoil and water use. The non-renewable energy products emergy includes raw coal, crude oil, coke, crude salt, natural gas, nitrogen fertilizer, cement, glass, electricity generation, etc. I is the input emergy, including total imports, tourism income, imported energy, labor inputs, etc. O is the output emergy, including total exports. GDP is the gross domestic product, τ_h the emergy per unit labor and person the total regional population that year.

2.2.4. Quantification of input-output variables

(1) Direct energy input emergy

In a COGRCU project, direct energy inputs mainly include raw coal, fuel coal, naphtha, oilfield-associated gas and electricity. They need to be converted into solar emergy through emergy intensities based on the findings of Liu et al. [41] (see Equation (9)).

$$Emd = \sum_{i=1}^{n} Ed_i \times NCV_i \times tr_i \tag{9}$$

Where Ed_i is the ith direct energy consumption, NCV_i the average low calorific value of the ith energy and tr_i the emergy intensity of the ith energy or material.

(2) Indirect energy input emergy

Indirect energy inputs are mainly used for fixed asset acquisition and depreciation, among other costs [13]. The emergy per unit money calculated in this study is used to convert indirect energy inputs into solar emergy [53] (see Formula 10).

$$Emid = MO \times EMR$$

Table 1
Two-dimensional framework for EROI analysis.

Levels for energy inputs	Boundary for energy outputs		
	Extraction	Processing	End-use
Direct energy and material (d)	$EROI_{1,d}$	$EROI_{2,d}$	$EROI_{3,d}$
Indirect energy and material (id)	$EROI_{stnd}$	$EROI_{2,id}$	$EROI_{3,id}$
Indirect labor consumption (lab)	$EROI_{1,lab}$	$EROI_{2,lab}$	$EROI_{3,lab}$
Auxiliary services consumption (aux)	$EROI_{1,aux}$	$EROI_{2,aux}$	$EROI_{3,aux}$
Environmental consumption (env)	$EROI_{1,env}$	$EROI_{2,env}$	$EROI_{3,env}$

$$= MO \times \frac{U}{GDP} \tag{10}$$

Where MO is a monetary form of energy input and *EMR* the emergy per unit money.

(3) Labor input emergy

The COGRCU project can function with the input of human resources. A year's work means that all emergy of an employee's year goes into the job. The emergy per unit labor calculated in this study is used to convert labor input into solar emergy [53] (see Equation (11)).

$$Em_{lab} = Q_p \times \tau_h \tag{11}$$

Where Q_p is the number of employees and τ_h the emergy per unit labor.

(4) Environmental governance input emergy

This study presents the scope of urban eco-economic loss emergy accounting based on the analysis of Liu et al. [41,55]. It calculates the environmental input emergy of the COGRCU project based on the study of [16]. Equations (12)–(17) show the specific calculation.

$$Em_{env} = Em_{ap} + Em_{wp} + Em_{disab} + Em_{eco} \tag{12}$$

$$Em_{ap} = \sum_{i=1}^{n} (N_{kinetie\ ,\ air} \times tr_{wind})_i$$

$$= \sum_{i=1}^{n} \left(d \times \left(\frac{AW_i}{c} \right) \times v_{wind}^2 / 2 \right) \times tr_{wind} \tag{13}$$

$$Em_{wp} = \sum_{i=1}^{n} (N_{kinetie\ ,\ water} \times tr_{water})_i + \sum_{i=1}^{n} (N_{chem\ ,\ water} \times tr_{chem\ ,\ water})_i$$

$$= \sum_{i=1}^{n} \left(\rho \times \left(\frac{WW_i}{c} \right) \times v_{water}^2 / 2 \right) \times tr_{water} + M_{water} \times G \times tr_{chem\ ,\ water} \tag{14}$$

$$Em_{disab} = \sum_{i=1}^{n} m_i \times DALY_i \times \tau_h \tag{15}$$

$$Em_{eco} = \sum_{i=1}^{n} m_i \times PDF(\%)_i \times E_{bio} \tag{16}$$

$$E_{bio} = \frac{K}{S} \tag{17}$$

Where $N_{kinetie,water}$ is the hydrokinetic emergy needed to dilute pollutants; tr_{water} the emergy intensity per unit of the water flow; v_{water} the velocity of the water flow; ρ the density of water; WW_i the emission of the water pollutant I; N_{chem} the chemical energy that can be used in water; $tr_{chem,water}$ the conversion rate of the chemical potential of water; M_{water} the total amount of water used in the chemical reaction; *G* the Gibbs free energy of water; $N_{kinetie,air}$ the wind emergy required to dilute pollutants; tr_{wind} the emergy intensity per unit of wind; v_{wind} the annual average local wind speed; d the density of air; AW_i the emission of air pollutant *i*; *c* the 'tolerable concentration' of the pollutant as defined by law or confirmed by scientific research (generally taken as background concentration); m_i the mass of pollutant i; $DALY_i$ the impact factor for pollutant i in the Eco-indicator 99 assessment framework; *DALY* the total number of years of life lost from the onset of illness to death; One *DALY* the amount of physical health lost per unit mass of pollutants for a given person for one year or 0.1 years for ten people; *PDF (%)* the potential species extinction rate; E_{bio} bio-resource emergy per unit area; *K* the total emergy of agriculture, forestry, livestock and fisheries and *S* the area of the study region.

(5) Project outputs

The COGRCU project can produce various kinds of energy chemicals. However, the emergy intensities of energy chemicals calculated in the existing literature is scarce. Calculating emergy flow in a typical chemical production system is challenging because it involves various interrelated steps in the reaction, separation, heating and cooling processes and a wide range of material inputs, energy recovery and product outputs. In addition, the complexity of the internal structure of chemical production systems and opaque and incomplete energy conversion rules make it more challenging to assess the emergy of the final products. Mu et al. [56] developed an emergy assessment model for a chemical production system. They evaluated the emergy of the output products using 30,000 tons of polyethylene process per year as an example, which showed an emergy of 2.16×10^{15}sej per unit of polyethylene. However, in this study, there are as many as eighteen products and by-products. The output emergy calculated based on a particular process are not suitable. In addition, differences in raw material prices and staff wages in different regions may lead to differences in the value of the same finished product. Therefore, this study uses the selling price of energy chemicals multiplied by the production volume and then converts it by the emergy per unit money, which is a more appropriate method for determining the project output emergy. It can be seen that the severe lack of emergy intensity of energy chemicals will constrain this study's subsequent application and promotion to some degree. Furthermore, while this paper proposes that multiplying the sales price of various energy chemicals by their outputs and converting them to solar emergy via regional emergy per unit money is considered to be a more realistic representation of the emergy of the project, mechanisms grounded in emergy theory require further examination in future studies.

2.2.5. Cost-benefit analysis

The main objective of energy and chemical enterprises is to gain profit. The Fuxian COGRCU project launched into commercial operation in July 2020. Therefore, this study uses a CBA to calculate the net benefit and benefit-to-cost ratio from 2020 to 2021 (see Formula 18).

$$\frac{B}{C} = \frac{\sum P_{Main\ products} \times Q_{Main\ products} + \sum P_{by-product} \times Q_{by-product}}{\sum C_{common} + C_{tax} + C_{env}} \tag{18}$$

Where B is the total income; C the total cost; $P_{Main\ products}$ the unit price of the main products; $Q_{Main\ products}$ the output of the main products, in particular, polyethylene, polypropylene, ethylene propylene rubber, butanol, etc; $P_{by-product}$ the unit price of by-products; $Q_{by-product}$ the output of the by-products, in particular, C4 fractions, C5 fractions, sulfur, ammonium sulfate, cracked heavy oil, etc; C_{common} the recurrent expense, in particular, operating costs, management expenses, sales expenses, financial expenses, R&D expenses, etc; C_{tax} the sum of all kinds of taxes, in particular, value-added tax, resources tax, etc; and C_{env} the environmental treatment cost, which is the cost invested by the project for environmental governance. If $\frac{B}{C} > 1$, then project is considered feasible. Otherwise, it is relatively high risk [57].

2.2.6. Combination of EmEROI and CBA results

There are nine combinations of EmEROI and CBA results for the COGRCU project. If EmEROI >1:1 and B/C > 1, the project's output emergy ratio to the input emergy is greater than one. In this case, there will be a energy surplus for economic and social development. The project is economically viable and should be encouraged to develop. If EmEROI <1:1, B/C > 1, there is no energy surplus; the net energy supply for economic and social development is negative and still needs large amounts of energy to sustain the project's production. However, it is economically viable. It usually does not exist; if it does, it is a form of extensive production that seeks economic benefits at mass energy expense. If EmEROI >1: 1 and B/C = 1 or EmEROI >1:1 and B/C < 1, it can provide net energy. However, the net benefits are zero or negative, which is riskier and may be due to poor project management, which leads to high operating costs and should improve project management and optimize costs. If EmEROI = 1:1, B/C = 1 or EmEROI = 1:1, B/C < 1, that is an energy equilibrium point between output and input, then the net energy available for economic and social development is zero, the net benefits are zero or negative, and should carefully implement the production. If EmEROI = 1:1, B/C > 1, the projects were crude production and should make efforts to improve their energy efficiency. If EmEROI <1:1 and B/C = 1 or EmEROI <1:1 and B/C < 1, then the project is not feasible except for the national strategic energy reserves project.

2.3. Data sources and processing

This study uses data from the China Energy Statistical Yearbook, the Yan'an Statistical Yearbook, and the National Standard of Pollutants for the Petroleum Chemistry Industry, relevant literature and field research. The raw data of total import, tourism income and export emergy from the Yan'an Statistical Yearbook are all monetary quantities that needed to be converted according to the emergy per unit money. However, data on the emergy per unit money needs to be available first. Therefore, calculating the total emergy of Yan'an City and dividing it by GDP is essential. In addition, due to the limitation of data sources, no data on the renewable environmental resources emergy in Yan'an City was obtained. The proportion of renewable environmental resources emergy in the total emergy is less than 0.07%, considering that the renewable environmental resources emergy in Yan'an City is four orders of magnitude lower than that of renewable natural resource products in the existing literature. Moreover, annual changes in renewable environmental resources are minimal and do not affect the calculation of R [54]. As a result, the renewable environmental resources emergy was obtained from the study of Mu et al. [54]. The emergy per unit money of Yan'an City was calculated based on the studies of [41,58,59] and the N, I, O and GDP data was primarily obtained from the Yan'an Statistical Yearbook.

Most existing studies use the method of Hu et al. [13] to calculate the indirect energy input emergy by industrial energy intensity, which implies that each unit of indirect energy input contains the same amount of energy as industrial energy intensity. However, industrial energy intensity is the average inclusion energy of the industrial sector; thus, multiplying indirect energy inputs by industrial energy intensity to reflect the inclusion energy of indirect energy is relatively inaccurate. Therefore, this study calculates the total emergy of Yan'an City from 2019 to 2021 based on the renewable resource emergy, non-renewable resource emergy, input and output emergy from the study of Liu et al. [41,55]. Afterward, the emergy per unit labor of Yan'an City from 2019 to 2021 is calculated by dividing the total emergy by population. Bio-resources emergy per unit area is calculated by multiplying the agriculture, forestry, animal husbandry and fishery output value by emergy per unit money and then dividing by the area of Yan'an City. Various cost data are obtained from enterprise field research.

In order to calculate the direct energy input emergy, this study sets the emergy benchmark at 15.83 × 10^{24} sej/a, tr_i obtained from the Handbook of Emergy Evaluation [60] and multiplied by 1.68. The energy consumption data and Q_p were obtained from the enterprise field research and NCV_i from the China Energy Statistics Yearbook. τ_h was calculated by this study. To calculate environmental governance input emergy, emission data of various pollutants were obtained from the enterprise field research. The project site's average annual wind speed and flow velocity were obtained from the China Meteorological Science Data Sharing Service Network. The 'tolerable concentration' of pollutants, as prescribed by law or confirmed by scientific research, was obtained from the National Emission Standards for Petrochemical Pollutants. Ecological and human influencing factors of pollutants, including potential losses of DALYs and species PDFs, were obtained from the Eco-Indictor 99 classification [61]. The outputs of products and by-products, selling prices, operating costs, management expenses, financial expenses, R&D expenses, taxes and environmental governance costs arise from enterprise field research.

3. Results

3.1. Emergy intensities of Yan'an city

The results of the emergy intensities of Yan'an City are the basis for the subsequent calculation of the EmEROI of the Fuxian COGRCU project. The emergy per unit money, emergy per unit labor and the bio-resources emergy per unit area is used to convert the output energy chemicals, indirect energy input, labor input and environmental governance input into solar emergy [16,53,54] and, thus, to calculate the EmEROI of the COGRCU project. Emergy intensities from the existing literature are usually replaced by previous studies' emergy intensities [16]. However, on the one hand, these data are not measured for the studied object. On the other hand, the data are relatively old, which will reduce the reliability of the research results to a certain extent. In this paper, we do not directly use emergy intensity in prior literature. Still, based on the actual situation of Yan'an City, we measured the various emergy intensities from 2019 to 2021 based on the study of [55], which will improve the reliability of the research results to some extent. Table 2 shows the total emergy, emergy per unit money, emergy per unit labor and the bio-resources emergy per unit area of Yan'an City as calculated in Equations (6)–(8) and Equation (17). The total emergy of Yan'an City in 2019, 2020 and 2021 was 1.34 × 10^{25}sej, 1.40 × 10^{25}sej and 1.52 × 10^{25}sej, respectively. These results are similar to this previous study [54]. The emergy per unit money was 8.05 × 10^{13} sej/$, 8.76 × 10^{13} sej/$ and 7.56 × 10^{13} sej/$, respectively. The emergy per unit labor was 5.73 × 10^{18} sej/person, 6.00 × 10^{18} sej/person and 6.49 × 10^{18} sej/person, respectively and the bio-resources emergy per unit area was 5.53 × 10^{13} sej/m^2, 7.79 × 10^{13} sej/m^2 and 8.42 × 10^{13} sej/m^2, respectively. Such results indicate a positive economic and social development trend in Yan'an City.

3.2. EmEROI of the Fuxian COGRCU project

3.2.1. EmEROI and energy efficiency

Based on Equations (1)–(17), the average standard EmEROI, EmEROI with labor inputs added to the standard EmEROI, EmEROI with labor and environmental governance inputs added to the standard EmEROI of the Fuxian COGRCU project in 2019, 2020 and 2021 were 17.44:1, 11.84:1 and 11.07:1, respectively. It can be seen that the EmEROI decreases with the increase in the types of input factors [13,16]. The above values in 2019 were 48.03:1, 22.27:1 and 19.48:1 with 97.92%, 95.51% and 94.87% of the output emergy used to promote economic and social development, respectively; in 2020, 12.95:1, 10.25:1 and 9.84:1 with 92.28%, 90.25% and 89.84%, respectively and in 2021, 8.53:1, 7.27:1 and 7.07:1 with 88.28%, 86.24% and 85.86%, respectively. Based on the above data, the project has high-energy efficiency and the output emergy is higher with less emergy consumed as an input. As a result, the COGRCU project can be seen as good practice for green and low-carbon transformation and upgrading energy and chemical enterprises in

Table 2
The results of the emergy intensities calculations of Yan'an City.

Items	Year		
	2019	2020	2021
R (sej)	1.29 × 10^{25}	1.38 × 10^{25}	1.49 × 10^{25}
N (sej)	1.60 × 10^{23}	1.68 × 10^{23}	1.82 × 10^{23}
I (sej)	2.89 × 10^{23}	7.34 × 10^{22}	7.93 × 10^{22}
O (sej)	6.56 × 10^{20}	4.43 × 10^{20}	4.79 × 10^{20}
U (sej)	1.34 × 10^{25}	1.40 × 10^{25}	1.52 × 10^{25}
Q_p (person)	2.34 × 10^{6}	2.34 × 10^{6}	2.34 × 10^{6}
GDP ($)	1.66 × 10^{11}	1.60 × 10^{11}	2.00 × 10^{11}
τ_h (sej/person)	5.73 × 10^{18}	6.00 × 10^{18}	6.49 × 10^{18}
EMR (sej/$)	8.05 × 10^{13}	8.76 × 10^{13}	7.56 × 10^{13}
E_{bio} (sej/m^2)	5.53 × 10^{13}	7.79 × 10^{13}	8.42 × 10^{13}

Notes: N, I, O, Q_p, GDP and the renewable natural resources data in R from the Yan'an Statistical Yearbook, the renewable environmental resources data in R from the literature [54] and the rest of the data were calculated by this paper.

resource-based cities.

As shown in Table 3, The standard EmEROI, EmEROI with labor inputs added to the standard EmEROI, EmEROI with labor and environmental governance inputs added to the standard EmEROI of the Fuxian COGRCU project from 2019 to 2021 declined by 58%, 43% and 40% on average per annum, respectively. It shows a downward trend in energy efficiency but above the 1:1 breakeven point, which is similar to earlier studies [13,16,29,34]. In other words, after considering various input emergy, for example, the input emergy of direct energy and indirect energy, the emergy consumed as a result of dilution of air pollution, the emergy consumed by dilution and decay of water pollutants and the emergy loss of local ecological resources caused by the acidification effect of SO_2 and NO_x, the emergy needed for transport, construction, industrial and agricultural sectors can still be generated. The ongoing production of the project is valuable for economic and social development in terms of energy flows.

3.2.2. Net energy analysis

From a thermodynamic point of view, any production process that outputs energy also consumes energy. Therefore, the sustainable energy supply should be the net energy remaining after making energy from energy, which is already confirmed by previous studies [15,21]. Based on Equation (4), it can be calculated that in 2019, 2020 and 2021, the net energy supply to economic and social development from the Fuxian COGRCU project will be 4.16×10^{23}sej, 5.07×10^{23}sej and 5.20×10^{23}sej, respectively, accounting for 95%, 90% and 86% of the total output emergy, with an average annual growth rate of 11.80%. These results are obtained after considering the emergy of direct and indirect energy, labor and environmental governance inputs. Therefore, the continued development of this project makes some sense from an energy flow. Although EmEROI with labor and environmental governance inputs added to the standard EmEROI decreased from 19.48:1 in 2019 to 7.07:1 in 2021, the output value of energy chemicals of the Fuxian COGRCU project increased by nearly 1.5 times from 758.84 million US dollars in 2019 to 111,240.31 million US dollars in 2021. In particular, the upstream raw material prices declined significantly in 2020 due to the Covid-19 pandemic, with the average price of energy chemicals decreasing by approximately 6% compared to 2019. The Fuxian COGRCU project produced 1.16 million tons of energy chemicals in 2020, an increase of 29% from 2019, amidst a surge in demand for products, such as medical masks, due to the pandemic. Eventually, the output value increased from 758.84 million US dollars in 2019 to 894.12 million US dollars in 2020 due to the interaction of price and production. In 2021, prices of upstream raw materials, such as raw coal, have significantly increased due to several factors, such as unfinished imports of 100 million tons of coal from Australia. As a result, the average price of energy and downstream chemicals has increased by approximately 44.40% compared to 2020. Due to the interaction of price and output, the output value of energy chemicals increased from 894.12 million US dollars in 2020 to 1112.40 million US dollars in 2021, with the output emergy increasing faster despite the decrease in EmEROI, which ultimately increased net energy. The net energy will provide the raw materials and materials required for production and operation in the energy, industrial, transport, construction, residential living, medical and other sectors.

3.2.3. Input emergy analysis

Based on Equations (9)–(16), the input emergy of direct energy, indirect energy, labor and environmental governance in 2019 was 6.54×10^{21}sej, 2.60×10^{21}sej, 1.06×10^{22}sej, 2.83×10^{21}sej, respectively. The above values in 2020 were 6.97×10^{21}sej, 3.66×10^{22}sej, 1.15×10^{22}sej, 2.32×10^{21}sej, respectively, and in 2021 were 6.32×10^{21}sej, 6.46×10^{22}sej, 1.23×10^{22}sej, 2.34×10^{21}sej. Fig. 3 shows that the total input emergy of the Fuxian COGRCU project increased from 2.25×10^{22}sej in 2019 to 8.56×10^{22}sej in 2021, nearly a threefold increase. This increasing trend shows that the input emergy required for the production and operation of the project is increasing, and this increase is mainly attributed to indirect energy inputs, such as new fixed assets investment and accumulated depreciation of fixed assets. Such findings are similar to the previous study [16] and reveal that the project should strengthen input management, especially to control the costs of various types of equipment acquisition, maintenance and repair, and human resource management to reduce indirect energy and labor input emergy. The contribution of each input emergy to EmEROI ranked as follows: indirect energy, labor, direct energy and environmental governance inputs account for an average of 38.15%, 23.80%, 13.75% and 5.18% of the total input emergy, respectively. Specifically, the labor and environmental governance input emergy accounted for 46.90% and 12.55% in 2019; direct and indirect energy input emergy accounted for 40.55%. The indirect energy input emergy accounts for 11.53%. Because the indirect energy input emergy consists primarily of new investment and accumulated depreciation of assets throughout the project, the increase in fixed assets will affect the indirect energy input emergy in the current year. Therefore, the depreciation value of the indirect energy input emergy would increase in the future until the fixed assets reach the planned fifteen years of use. The Fuxian COGRCU project was in a trial operation phase until it launched into commercial operation in July 2020. There will be no further investment in 2019 but only in 2020 and 2021 for 8.34 and 19.46 million US dollars, respectively. From 2020 to 2021, the direct and indirect energy input emergy accounts for over 75% of the total input emergy, including 12.16% and 7.38% of the direct energy input emergy, respectively. Indirect energy input emergy is 3.4×10^{22}sej and 6.21×10^{22}sej, which accounts for

Table 3
Results of EmEROI calculations for the Fuxian COGRCU project.

Year	The standard EmEROI	EmEROI with labor inputs added to the standard EmEROI	EmEROI with labor and environmental governance inputs added to the standard EmEROI
2019	48.03:1	22.27:1	19.48:1
2020	12.95:1	10.25:1	9.84:1
2021	8.53:1	7.27:1	7.07:1

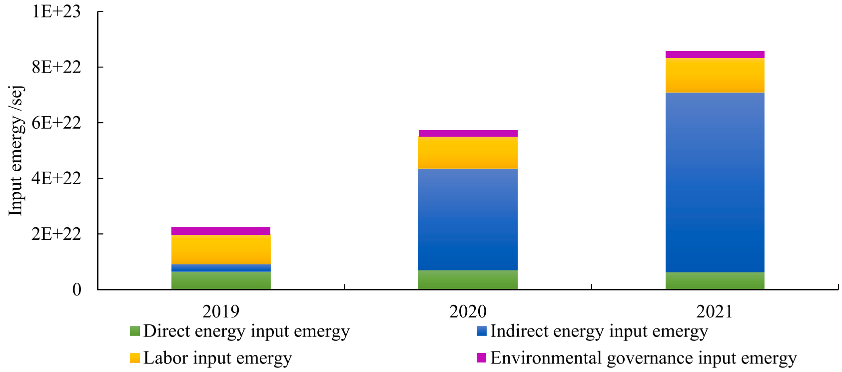

Fig. 3. Input emergy of the Fuxian COGRCU project.

63.81% and 75.5%, respectively, compared to 2019. The high proportion is mainly due to the accumulated depreciation of fixed assets and new investments in the current year, which resulted in the decrease of EmEROI with labor and environmental governance inputs added to the standard EmEROI to 49.50% and 63.71%, respectively, compared to 2019. The labor input emergy is 1.15×10^{22}sej and 1.23×10^{22}sej, which accounts for 19.99% and 14.39% of the total input emergy, respectively. The average labor input emergy from 2019 to 2021 is 1.14×10^{22}sej, an average annual growth rate of 8%. This can be explained by the fact that although the COGRCU project is more intelligent and require higher comprehensive quality of personnel, the projects are usually located far away from residential areas, making it difficult to bring in talent. The environmental governance input emergy is 2.32×10^{21}sej and 2.34×10^{21}sej, which accounts for 4.05% and 2.74% of the total input emergy, respectively. The low percentage does not imply that the level of environmental pollution of the Fuxian COGRCU project is low. Based on the survey, CO_2 from the Fuxian COGRCU project is emitted directly into the atmosphere with no treatment other than its direct usage during production. Therefore, obtaining or considering this part of the CO_2 emissions data is difficult. In addition, the energy required by the natural environmental system for the self-decomposition of pollutants is measured based on the national minimum standards for the emissions of pollutants from chemical enterprises. The combination of these factors means that the environmental governance input emergy is still somewhat underestimated. Thus, obtaining data is a critical constraint for this study. Furthermore, in the background of 'double carbon', energy and chemical enterprises will be faced with a shutdown at any time if they are not able to solve the problem of carbon dioxide emissions effectively; for this reason, energy and chemical enterprises should place a high value on carbon emissions and thoroughly solve the ecological and environmental issues that affect the project.

3.3. *Results of the CBA*

This study uses CBA to measure the Fuxian COGRCU project's net benefits and benefit-to-cost ratio from 2020 to 2021 based on the EmEROI analysis. Costs refer to costs incurred during the production and operation. The routine expenses refer to operating costs, administrative expenses, sales expenses, financial expenses, R&D expenses, etc. For instance, operating costs refer to raw materials, fuel, ancillary materials, power, staff salaries, equipment maintenance, depreciation costs, etc. Required for regular project operation. Financial expenses refer to short-term borrowing interest on working capital and long-term borrowing interest on construction investment funds. Ancillary expenses refer to taxes and fees. Environmental governance expenditure refers to investments in environmental treatment, such as solid waste disposal costs. Benefits refer to the income from the central business, such as from the sales of

Table 4
Cost-benefit table for the Fuxian COGRCU project from 2020 to 2021. (Million US dollars).

Cost benefit types	Year	
	2020	2021
Routine expenses	376.07	870.15
Operating costs	322.65	759.68
Management fees	10.52	25.17
Selling costs	3.17	5.36
R&D expenses	–	–
Financial costs	39.73	79.95
Various taxes	2.02	28.36
Environmental treatment fees	0.97	2.78
Income from main operations	396.64	957.99
Net benefits *	17.57	56.70
Benefit-to-cost ratio (B/C)*	1.05	1.06

Note: *is calculated from this study, the remainder of the data comes from the enterprises' financial statements.

products and by-products. Table 4 shows that the Fuxian COGRCU project'costs are primarily concentrated in operating costs, accounting for 85.79% and 84.29% of the total costs in 2020 and 2021, respectively. The net benefits of the project in 2020 and 2021 are 17.57 million US dollars and 56.70 million US dollars, respectively, according to Equation (18), with a benefit-to-cost ratio of 1.05 and 1.06, respectively. This indicates that the project is economically feasible. However, some projects with positive economic benefits are realized based on massive energy consumption. The energy efficiency of these projects is usually extremely low, resulting in a huge waste of energy and causing externalities such as ecological damage and loss of health of the population. Therefore, when evaluating a production activity, it is essential to consider both monetary and energy flows [62].

3.4. Analysis of EmEROI and cost-benefit mix results

Sections 3.2.1 and 3.2.2 indicate that the project has a high-energy efficiency. The project's benefit-to-cost ratio is greater than one, indicating it is economically viable. Therefore, it belongs to a combination of EmEROI >1:1 and B/C > 1 scenarios and should be further developed. This study differs from previous studies [16,23]. It conducts a comprehensive assessment of the COGRCU project in terms of energy and monetary flows, while Chen et al. [16] and Kong et al. [23] emphasized evaluation of projects in terms of energy flows. Chen et al. [16] calculated a decrease in EmEROI of the Daqing Oil Field from 6.30 in 2001 to 3.60 in 2012, which is different from the calculation conducted in this study. There are several reasons for this: First, the two fields of study differ. These cities have different resource endowments, economic and social development levels, industrial structures and wage and price levels. Second, the selection of object and output boundaries is different. This and Chen et al. [16] examined the COGRCU projects and oil and gas extraction, respectively, with output boundaries in the end-use and extraction phases [19]. Third, the selection of emergy intensity is different between them. Furthermore, Chen et al. [16]only consider direct energy consumption emissions in calculating the environmental impact. This study considers more factors when measuring environmental impacts; see equation (5). Therefore, a third-party environmental assessment agency is needed to examine the environmental impact of the COGRCU projects.

Kong et al. [23] measured the standard EROI of China's Shenhua coal-to-oil project. They were again significantly lower when CCS technology inputs were considered. This paper and Kong et al. [23] used energy and chemistry projects as the research topics, but the findings differ. First, the research area and methods differ: this study examines EmEROI and Kong et al. [23] examined EROI. Second, the input hierarchy is different: this study considers direct energy, indirect energy, labor and environmental governance, whereas Kong et al. [23] did not consider labor and environmental governance inputs. Third, the two studies have different energy and chemical output categories and energy levels, such as liquefied petroleum gas, gasoline, diesel and electricity from China's Shenhua coal-to-oil project and four by-products, such as benzene, phenol, naphtha and xylene. The Fuxian COGRCU Project generated eighteen products and by-products. According to the emergy theory, the olefins produced by the COGRCU project have higher energy grades than those in the coal-to-oil project. Furthermore, Kong et al. [23] found that the net energy of the project supplied to society is extremely low or perhaps even negative under various circumstances. Therefore, the government and investors are advised to be cautious in their development. Indeed, China's external dependence on oil and natural gas has been as high as 74% and 45%, respectively, threatening China's energy security to some extent. Depending on China's domestic conditions and energy endowment characteristics, coal-to-oil technology should be used as a strategic energy reserve to cope with a potential energy crisis and ensure energy security. Therefore, Shenhua Group should improve the energy efficiency of coal-to-oil projects while extending the coal-to-oil industry chain, thus, the economic benefits of the projects.

4. Discussion

There are often differences between the actual benefits of the COGRCU projects and those anticipated in previous assessments. However, it is often difficult to identify the causes of the differences. Therefore, a post-evaluation methodology of the COGRCU projects is proposed to help energy and chemical enterprises identify the key factors that constrain the energy return on energy inputs to maximize the project's expected benefits and optimize management and the transformational development of those resource-based urban cities as well as urban governance. The case study of the YC Group's Fuxian COGRCU project shows that the project has high energy efficiency and economic feasibility. Indirect energy and labor inputs need to optimize further to improve the project's energy efficiency. Operating costs are the key factors contributing to improving the project's economic benefits and environmental governance inputs have the least impact on EmEROI. Based on these results, this study recommends the following policies based on the practicalities of the project.

First, the results show that the net energy used to promote economic and social development by the Fuxian COGRCU project from 2019 to 2021 increased at an average annual rate of 11.80%, accounting for more than 85% of the total output emergy and the benefit-to-cost ratio from 2020 to 2021 is greater than one. Thus, the project has high-energy efficiency and economic feasibility. Therefore, the state, Shaanxi Province and Yan'an City governments should strengthen their policies to support the COGRCU projects by advancing the formulation and revision of fiscal and tax policies to promote the high-quality development of energy and chemical enterprises in Shaanxi Province. For example, the government should revise the incentives for energy and chemical enterprises to actively develop COGRCU projects by lowering tax rates, prices, investment and financing, subsidies [63], and other policy tools and combinations. In addition, technology and management innovation should be promoted to accelerate the development of energy and chemical enterprises into safe, efficient, environmentally friendly and low-carbon enterprises. The state and the provincial government should speed up the construction of a high-end chemical energy base in northern Shaanxi. Effectively link upstream and downstream industries of energy chemical, advance the formation of scale economies in industrial clusters, build a high value-added energy and chemical brand in northern Shaanxi, further enhance its influence in international and domestic markets and create a good market environment for high-quality development of the COGRCU projects.

Second, the indirect energy input emergy has the most significant effect on EmEROI. In addition, the operating costs, such as raw materials, fuel, ancillary materials and electricity, wages, equipment maintenance and depreciation, account for over 84% of the total cost. As a technology-capital-resource-intensive project, a scientific and reasonable investment budget is crucial to stabilize the operation and optimization of the economic benefits of the project. Therefore, on the one hand, YC Group should conduct a scientific analysis of the advantages and disadvantages of existing investment plans and flexibly, timely and rationally adjust the investment plan based on the market environment, production capacity, process technology and financial situation to optimize the resource allocation scheme. On the other hand, the refined management of existing assets needs to be strengthened to avoid the idleness of fixed assets and improve the utilization of existing assets by improving energy efficiency to reduce the use of raw materials, fuels and auxiliary materials, effectively reducing the acquisition cost of fixed assets and the maintenance cost of equipment [64]. For example, it should strengthen the project equipment management to reduce the procurement and maintenance costs of various types of equipment by designing and optimizing equipment configuration based on capacity needs, cost comparison of upgrading old equipment and acquiring new equipment. Moreover, based on the functional requirements of equipment, comparing technical performance, price and environmental protection to determine the best equipment to reduce equipment acquisition and, thus, depreciation costs. In terms of equipment use, equipment managers, operators and maintenance personnel should be trained in pre-employment skills in strict compliance with the maintenance manuals or guidelines of equipment manufacturers and the maintenance systems of energy and chemical enterprises of various types of equipment, such as special and general-purpose equipment. In particular, equipment operators should strictly operate according to the operating instructions and procedures to reduce equipment damage caused by misuse. In addition, the project equipment management should also improve the equipment scheduling management and develop standards for energy and chemical enterprises for equipment repair and maintenance costs, such as accounting standards and single machine and vehicle accounting standards and systems. These can be used for regular appraisals based on indicators, such as fuel and power costs, repair and maintenance fees, labor costs and the number of equipment configurations to reduce equipment failure rates.

Third, human resource management should be optimized in the COGRCU projects, including equipment operation, maintenance, and management personnel. This study observes that the labor input emergy in the Fuxian COGRCU project was second only to indirect energy in the total input emergy and continues to grow at an average annual rate of 8%, which is one of the critical constraints to improve energy efficiency further. Therefore, human resource management should extensively use modern human resource management methods to improve salaries, shareholding systems, and staff performance appraisals to increase labor productivity and work quality and reduce labor intensity effectively, thereby reducing the labor input emergy [65]. In addition, energy and chemical enterprises should actively attract and train high-end professionals and technical and complex high-level talents from the energy and chemical industry to form an internal think tank to promote high quality project development. Cooperation in government, industry, academia, research, application and finance will be strengthened around the significant issues hindering the technological progress of COGRCU projects. Research and development should also be enhanced to generate early results and rapid transformation to achieve win-win development.

Last, the environmental assessment results of the COGRCU projects should combine with tax incentives to stimulate energy and chemical enterprises as well as resource-based urban cities' green and sustainable development. Under the 'double carbon' background, the ecological environment problem will be the main bottleneck in restricting the development of the energy and chemical industry and resource-based urban cities [66]. If the relevant environmental protection requirements are not met, the COGRCU projects can be shut down and held accountable at any time. The remaining CO_2 is emitted directly into the atmosphere without treatment, which contradicts the 'double carbon' target and related environmental policies and regulations. Therefore, the state and relevant government agencies should require energy and chemical enterprises to set up specialized agencies responsible for monitoring the various types of pollutant emission data. Encourage third-party environmental assessment institutions to regularly compile annual environmental pollution assessment reports of energy and chemical enterprises and report them to relevant departments on time. In addition, the government of Shaanxi Province and Yan'an City should take the environmental assessment results as an essential basis for evaluating the heads of energy and chemical enterprises and whether enterprises and cities can benefit from tax concessions, financial subsidies, and investments. In addition, according to the Shaanxi Total Carbon Emissions Action Plan, Yan'an City and energy and chemical enterprises should find a suitable decarburization plan as soon as possible and fundamentally address the carbon emissions problem.

5. Conclusions

This study presents a post-evaluation methodology of the YC Group's Fuxian COGRCU project to provide energy and chemical enterprises a basis to identify the constraints preventing them from fully realizing energy efficiency and economic benefits improvement, simultaneously helping YC Group to improve project management. It can also promote transformational development of these resource-based urban cities and urban governance. The existing studies have not fully considered the impacts caused by the project on the ecological environment and residents' health. They focus on a separate evaluation of one aspect, such as economic benefits or energy efficiency, which has resulted in differences between the evaluation results and the actual situation. Therefore, this study proposes a post-evaluation methodology of the COGRCU project based on the case study of YC Group's Fuxian COGRCU project in Fuxian County. The main findings from the study are as follows.

(1) Under the background of 'double carbon', energy and chemical enterprises in resource-based urban cities actively develop COGRCU projects, which greatly value economic and social development. The Fuxian COGRCU project has high-energy

efficiency and economic feasibility. The net energy provided to economic and social development is over 85%, with net benefits of 17.57 million US dollars and 56.70 million US dollars in 2020 and 2021, with a benefit-to-cost ratio of 1.05 and 1.06, respectively.

(2) Indirect energy and labor input emergy are the main factors contributing to improving the COGRCU projects' energy efficiency. The indirect energy and labor input emergy account for an average of 38.15% and 23.80% of the total input emergy, respectively and need to be optimized further to improve energy efficiency of the COGRCU projects.

(3) Operating costs are the main factors contributing to improving the COGRCU projects' economic benefits. From 2020 to 2021, the operating costs of the Fuxian COGRCU project were 322.65 million US dollars and 759.68 million US dollars, which account for 85.79% and 84.29% of the total project costs, respectively. Therefore, reducing operating costs is essential to improve the project's economic benefits further.

(4) Environmental governance inputs have the least impact on the EmEROI of the COGRCU project. Each input emergy's contribution to the project's EmEROI sequentially declines in indirect energy, labor, direct energy and environmental governance. Environmental governance input emergy only account for 5.18% of the total input emergy.

Based on these conclusions, this study proposes several policy recommendations that include strengthening policy support, such as advancing the formulation and revision of fiscal and tax policies, improving project assets and human resources management and increasing environmental governance. This study is applicable to evaluate energy efficiency and economic benefits in the post-evaluation of energy chemical projects in resource-based cities. However, the results or policy recommendations may not be universally applicable to energy and chemical enterprises in different cities outside Yan'an City. It is primarily due to differences in the total emergy, the emergy per unit money, emergy per unit labor, and bio-resources emergy per unit area, and project production process in different cities, resulting in different measured input and output emergy, the results or policy recommendations are different. Therefore, the post-evaluation methodology proposed in this study should be used to derive targeted results and adopt practical policy recommendations, considering the actual situation of energy chemical projects in different cities. Nevertheless, similar energy and chemical projects may still benefit from these recommendations to achieve quality development goals. Moreover, the scientific and accurate measurement of these emergy intensities is a laborious task, which partially influences the application of this method to some degree. However, the post-evaluation methodology of COGRCU projects proposed in this study is helpful for energy and chemical enterprises in different cities to identify the factors that greatly influence energy efficiency and economic benefits, and the method is applicable as long as enough data is available.

Author contribution statement

Linmei Cai: Performed the experiments; Wrote the paper.
Xiaoqian Song: Conceived and designed the experiments; Analyzed and interpreted the data.
Jinsuo Zhang: Conceived and reviewed the paper. Yebei Xing: Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We would like to thank all the editors and reviewers. We would like to thank the National Natural Science Foundation of China (Grant Nos. 72004130, 71273206), Shaanxi Provincial Social Science Federation Key Think Tank Project (2021ZD0998) and Shaanxi Provincial People's Congress Finance Committee Project (2022HZ1541) for their financial support. We would also like to thank Professor Fu Feng and his team from the School of Chemical Engineering of Yan'an University for providing us with the opportunity to make the data acquisition process of this study very smooth.

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