

## Circular economy for clean energy transitions: A new opportunity under the COVID-19 pandemic

Chang Su <sup>a,b,\*</sup>, Frauke Urban <sup>b</sup>

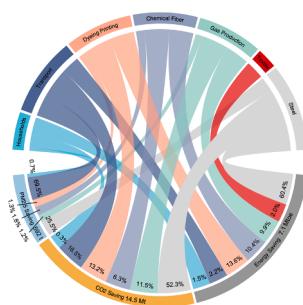
<sup>a</sup> Department of Energy Technology EGI, KTH Royal Institute of Technology, Brinellvägen 68, S-100 44 Stockholm, Sweden

<sup>b</sup> Department of Industrial Economics and Management INDEK, KTH Royal Institute of Technology, Lindstedsvägen 30, S-100 44 Stockholm, Sweden

### HIGHLIGHTS

- Clean energy transitions based on the circular economy (CE) are analysed for a town in China.
- This could reduce energy use, CO<sub>2</sub> emissions and PM<sub>2.5</sub> emissions compared to the BAU scenario.
- COVID pandemic is a new opportunity to introduce circular economy measures.
- Circular economy measures could accelerate clean energy transitions.

### GRAPHICAL ABSTRACT



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### ABSTRACT

This paper models the energy and emissions scenarios for a circular economy based clean energy transitions in a 140,000-population town in China, taking into account the new situation encountered by the COVID-19 pandemic. The modelled scenarios propose new clean energy transition roadmaps towards a sustainable urban system through the implementation of circular economy strategies. This is represented by the cascading use of industrial excess heat to form symbiosis between factories and to cover the growing building heat demand, as well as by the electrification of the transport sector and reusing the batteries for a second life as energy storage devices. The results show that for a circular economy scenario, during 2020–2040, an accumulated saving of 7.1 Mtoe final energy use (34%), a decline in 14.5 Mt CO<sub>2</sub> emissions (40%) and 592 t PM<sub>2.5</sub> emissions (43%) could be achieved compared with the business-as-usual scenario. The outcomes of the circular economy strategies are at least 7% better than the new policy scenario which simply has energy efficiency improvements. The outbreak of the COVID-19 tremendously impacts the socio-economic activities in the town. If taking the pandemic as an opportunity to enhance the circular economy, by 2040, compared with the scenario without introducing circular economy measures, the extra avoided final energy use, CO<sub>2</sub> emissions and PM<sub>2.5</sub> emissions could be 1.6 Mtoe (8%), 3.8 Mt (11%) and 229 t (17%) respectively.

\* Corresponding author.

E-mail address: [chang.su@energy.kth.se](mailto:chang.su@energy.kth.se) (C. Su).

## 1. Introduction

### 1.1. Background

The urban energy system of China is still heavily reliant on fossil fuels. The high consumption of coal and oil products by industry and transport have brought about significant carbon emissions and environmental pressures. A sustainable urban energy system is the national consensus from China's central level administration down to prefectures. Dense population characterises the urban areas of China. The associated fossil fuel energy system deters the implementation of sustainability and exacerbates climate change [1]. At the national level, China has enacted a number of policies to echo energy and environmental challenges [2], which reconciles with and contributes to international sustainable development frameworks such as the United Nations Framework Convention on Climate Change (UNFCCC) [3]. China aims to be carbon neutral before 2060 [4].

At subnational level, China's local governments and policy makers are facing the challenges to apply a holistic thinking paradigm to develop, design and manage the existing energy system, and gradually transform it to a smart and sustainable model [5]. In general, a desired future sustainable urban energy system should be optimized to reduce fossil energy consumption, while providing the required energy services to increase energy efficiency at competitive costs. The clean energy transition should also be able to mitigate climate change by maximizing renewable energy shares [6].

China has 20,000 prefectoral towns, in which 800 million people resides [7]. The economic activities and associated energy consumptions are huge. In order to achieve a sustainable energy system through clean energy transition for the towns, a pilot study was carried out on the administrative area of Meili Town in Jiangsu Province, southeast China. This paper therefore models the energy and emissions scenarios for a circular economy based clean energy transitions for Meili Town, taking into account the new situation encountered by the COVID-19 pandemic.

### 1.2. Case study area

The geographical location, administrative boundary, urban planning and basic socio-economic data of Meili Town are shown in Fig. 1. Meili Town is located at the geographical coordinates of 31°39'N, 120°44'E beside the Yangtze River, within Jiangsu Province of southeast China. It is 100 km west of the metropolitan of Shanghai. Meili Town is in the subtropical climate zone of China with abundant rainfall. Its annual ambient air temperature ranges from 0 °C to 38 °C. Meili has potential to deploy solar energy systems. But its wind energy potential is poor since its average wind speed is only about 5 m/s. In the fiscal year 2017, Meili Town had a population of 140,012 with a demographic growth rate of 0.4% annually. Meili Town has an administrative area of 80.74 km<sup>2</sup>, in which 47.72 km<sup>2</sup> is built up. A new urban planning of Living Zone (11.1 km<sup>2</sup>) and Industry Zone (8.8 km<sup>2</sup>) has been suggested by the local urban managing authority. Meili Town has been experiencing a significant increase in the regional GDP value, from a regional GDP of 6.98 billion CNY<sup>1</sup> in 2008 to 8.28 billion CNY in 2017 [8].

Meili Town urgently needs a diagnosis on its energy system and a viable clean energy transition plan. Local statistics show that Meili Town's economy is built on industry. Meili Town has a total of 96 industrial companies, among which steel and ironmaking, textile, dyeing-printing, chemical fiber, gas production and automobile account for the top energy consumers. Together they contribute to more than 50% of Meili's total GDP [10]. Though enjoying the prosperity of economy growth, Meili's industries are heavily reliant on coal for their heating and power needs. Therefore, Meili's energy intensity is as high as 0.115 kg oil equivalent per Chinese Yuan (kgoe/CNY), much higher than the

average energy intensity of China, which is around 0.018 kgoe/CNY [11]. Meili citizens are suffering from air quality issues brought by the energy intensive industries, particularly the steel industry. Meanwhile, Meili's current households are heated and cooled by air-conditioners, which are mainly powered by coal-based electricity. Meili has access to just 82 public transport buses. There is no other means of public transport available. A lack of sufficient public transport options further adds to pollutants emissions as citizens prefer to use their personal gasoline vehicles. As Meili's economy continues to grow and people's demand for energy services increase, enormous pressures are added on the environment and resources.

Recognizing the challenges, the Meili community is motivated to bring diversity to its energy mix, to reduce its dependence on fossil fuels while providing necessary services to its per capita energy demand. The Meili community also intends to increase its sustainability through circular economy and to implement new infrastructure and policy measures to curb carbon emissions as well as alleviate its air pollutants.

## 2. Literature review

A brief literature review on previous research works and the definition of circular economy adopted in this study are provided in this section.

### 2.1. Previous research

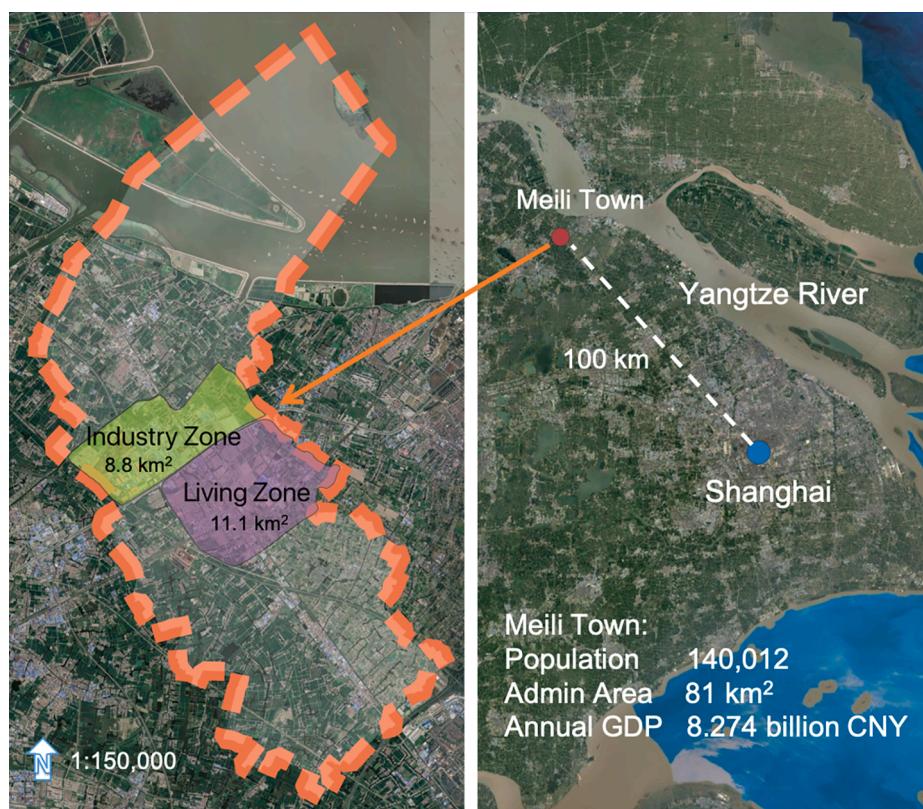
The decarbonization strategies in China have been discussed by many researchers. For example, Urban et al. [12] as well as Wang and Watson [13] studied the penetration of renewable energy in China and found that it could bring significant carbon emissions saving. This point is also proved by Su et al. in a study focusing on the space heating of the built-environment since it is a major source of urban air pollution in winter [14]. A decade or so ago, the economic growth of China was very high, coupled with population growth and heavy industrial activity, leading to rapidly rising emissions. Hence the business-as-usual cases of energy modeling scenarios back then indicated huge emission increases, which could however partly be mitigated by the large-scale increase in the share of hydropower, other renewable energy and nuclear power.

A few years later, ERI-NDRC published their roadmap to achieve emission reductions through high renewable energy penetration [15]. While huge improvements were being made in energy intensity, investments in renewable energy and ambitious climate policies came into place, the research focus in subsequent years was often related to whether or not emissions in China could be peaking before 2030 (see for example den Elzen et al. [16]; Duan et al. [17]; Guo et al. [18]). Recent research by Busby et al. [19] analyses decarbonisation strategies for China's industrial sectors according to their political/organizational feasibility and techno-economic feasibility. There is also a trend of applying interdisciplinary methodologies to provide decarbonisation solution packages for the building sectors of China [20]. Yuan et al. model energy and emission scenarios until 2050 and find that while the energy intensity reduction targets can be easily achieved, it will be more difficult to achieve emissions peaking and China's non-fossil energy targets [21]. In terms of circular economy measures, Ma et al. [22] have analysed the co-benefits of decarbonizing the Chinese steel sector. However, the focus of the Chinese steel industry is still mainly on energy efficiency improvements, and not on novel non-fossil technology such as hydrogen-based steel production [23].

### 2.2. The definition of the circular economy in this study

Circular economy is an umbrella concept which could mean different things to different domain experts. Kirchherr et al. gathered 114 circular economy definitions and systematically analyzed the concept. The authors define circular economy as an economic system that focusses on the reusing, recycling and recovering concepts, and operates at various

<sup>1</sup> 1 CNY ≈ 0.14 EUR.



**Fig. 1.** Administrative boundary of Meili (left); Meili relative location to Shanghai (right) [9].

levels towards sustainability [24]. Korhonen et al. pointed out that circular economy is a closed-loop cyclical process. It is an approach rather than a theory, which has the potential for future paradigmatic shifts that can consequently result in industrial transformations [25]. In this study, the definition of circular economy is within the set of the definitions given by previous studies but focuses more on the definitions related to energy or energy materials, represented by cascading use of energy, using renewable energy as well as recycling energy materials for energy purposes [26].

Many decarbonization strategies, advanced over time, can be promoted and included under the scope of the circular economy concept to form a new solution package. This paper therefore demonstrates measures to deliver a future low carbon sustainable energy system for Meili Town by implementing circular economy measures. Analysis is carried out for the energy demand side. Viable circular economy options (see Table 1) are used to generate scenarios considering industry, building and transport sector. Under the shade of the COVID-19 pandemic, the impacts from such black swan incidents are also included in the study.

In Meili Town, the current normal economy structure associated with the energy activities is described by a production-consumption-disposal model. The energy carrier or energy materials are produced locally or imported across Meili's administrative borders, then consumed by

different sectors in Meili and disposed when depleted. By implementing the energy associated circular economy measures, Meili Town could be transformed into a new circular economy mode, where the energy (primarily heat) is used cascadingly, energy materials recycled and reused and more renewable energy is penetrated and consumed. The comparison of a normal economy and a circular economy of Meili Town is illustrated in Fig. 2.

### 3. Modelling methodology and scenario development

The energy system analysis is performed using LEAP: The Low Emissions Analysis Platform software tool, for analyzing the decarbonisation of economies and industries. LEAP has been used in 190 countries, including to analyse Nationally Determined Contributions (NDCs) as part of countries' Paris Agreement commitments [36]. It is particularly useful in answering the 'what if' questions in scenario analysis.

#### 3.1. Description of the LEAP model

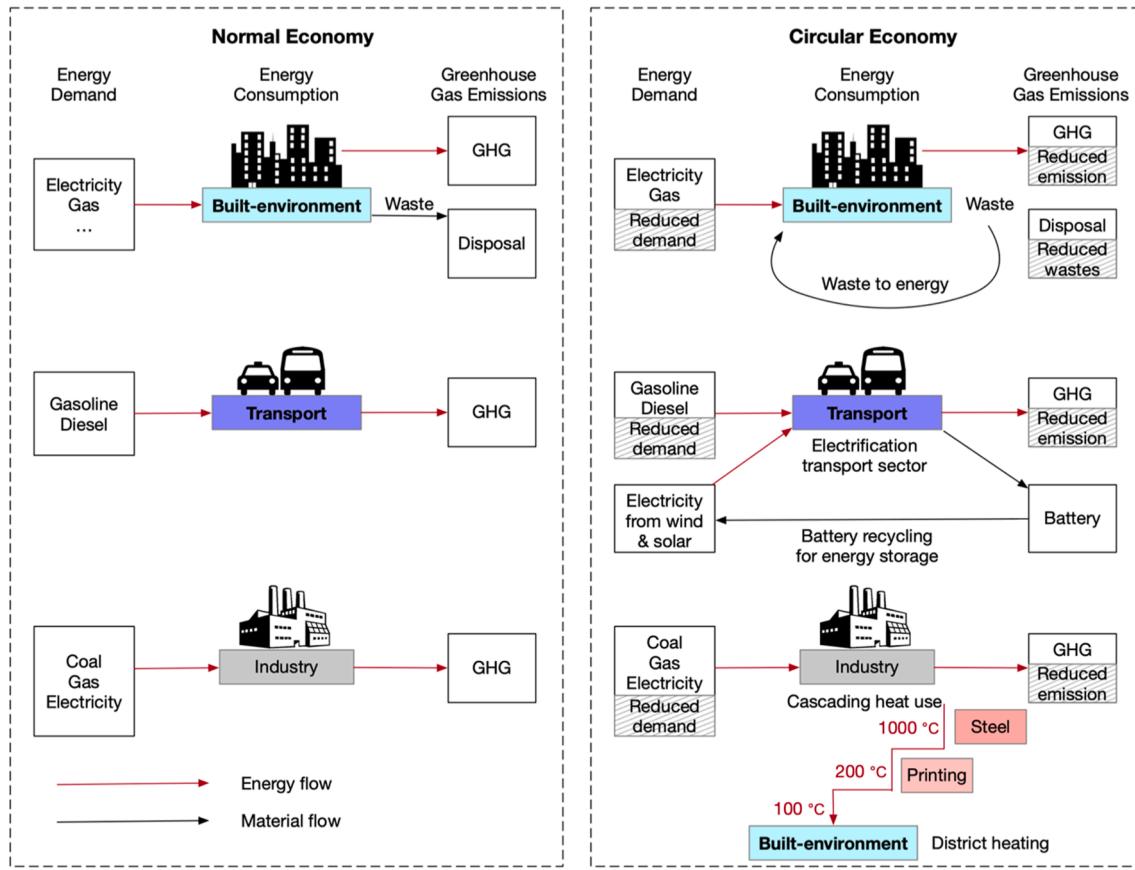
The LEAP model built in this study focuses on the energy demand side analysis. The modelling system boundary is chosen to be the administration boundary of Meili Town, which contains the energy activities that happen locally, as well as the policy measures enacted by Meili government targeting local industries and businesses. The scenarios' modelling time-step is on a yearly basis. Starting from the reference year 2019, the sectorial energy demand in the town is simulated at each time interval (1 year). At the end of each simulation step, the results of sectoral energy demand and environmental influences could be examined. The projection results end at 2040, which is to be inline with the IPCC climate change impact analysis [37].

Fig. 3 shows the LEAP model's schematics overview. The LEAP model analyses 3 main sectors or branches: Built-environment, Transport and Industry. Each sector further ramifies to sub-sectors or sub-branches to represent the energy services needed. Then, each energy

**Table 1**

A list of the various circular economy measures in each of the sectors in Meili Town.

Sector	Circular economy measures	Selected examples
Built-environment	Cascading energy use	[26,27]
	Waste to energy	[28,29]
Transport	Electrification	[18,30]
	Battery recycling	[31,32]
Industry	Cascading energy use	[27,33]
	Electrification	[18,34]
	Battery recycling	[31,35]



**Fig. 2.** Illustration of the difference between a normal economy and a circular economy for Meili Town.

service is covered by its technology options (quantified by Technology Activity Level), and the technology's fuel/energy consumption (quantified by Final Energy Intensity). The energy demand for one type of energy service could therefore be calculated by Eq. (1):

$$\text{Service's Energy Demand}_j = \sum_{i=1}^n \text{Activity Level}_i \times \text{Final Energy Intensity}_i \quad (1)$$

$i$  represents one type of technology under one energy service, e.g. Electric water Heater, which is under hot Water.

$j$  represents one type of energy service under one sub-branch, e.g. Hot Water, which is under Households.

$n$  represents the number of different technology options under one service.

Next, the energy demand for one sub-branch (e.g. Household) in one simulation step is the summation of all the energy services under this sub-branch (Eq. (2)).

$$\text{Sub Branch Energy Demand}_k = \sum_{j=1}^n \text{Service's Energy Demand}_j \quad (2)$$

$k$  represents one sub-branch, e.g. Households.

Except for analyzing the energy demand, Carbon Dioxide (CO<sub>2</sub>) emissions and Particulate Matter 2.5 (PM<sub>2.5</sub>) emissions are used as two other indicators to analyze the environmental impacts of each scenario. The calculation of the emissions is given by Eq. (3).

$$\text{Emissions}_k = \sum_{j=1}^n \left( \sum_{i=1}^n \text{Emission Factor}_i \times \text{Service Energy Demand}_i \right) \quad (3)$$

For LEAP model's current account which represents the situation of the fiscal year 2019, the input data including technology activity level and final energy intensity comes from the Meili Town authority, who has conducted an energy audit to investigate the current energy consumption in relation to the socio-economic and industrial activities. The data were collected and integrated from the town's statistics bureau, electricity bureau, transportation bureau, local industries' energy reports. Some incomplete data were integrated from other literatures and the consistency was checked. The data are listed in the tables of [Supplementary Material A](#) with corresponding references to the data sources.

Five scenarios of clean energy transitions are established and analyzed: business-as-usual scenario (BAU), new policy scenario (NP), circular economy scenario (CE), pandemic scenario without circular economy (PAN w/o CE) and pandemic scenario with circular economy (PAN w CE). The business-as-usual scenario assumes no new policies will be enacted, so as to serve as the reference case for comparisons. The new policy scenario projects the Meili energy system till 2040 considering the implementation of national and local policy decisions as well as other national ambitions. The circular economy scenario designs a new path for Meili to implement circular economy measures, then demonstrates how circular economy can help Meili shift its energy patterns and transform into a more sustainable mode. The pandemic scenarios reflect how the COVID-19 pandemic can affect Meili's transition trajectory, for both without and with the enhancements from circular economy measures.

In the scenario analysis, the Technology Activity Level and the Final Energy Intensity are the parameters that are varied to investigate the consequences of new energy policies, circular economy measures and

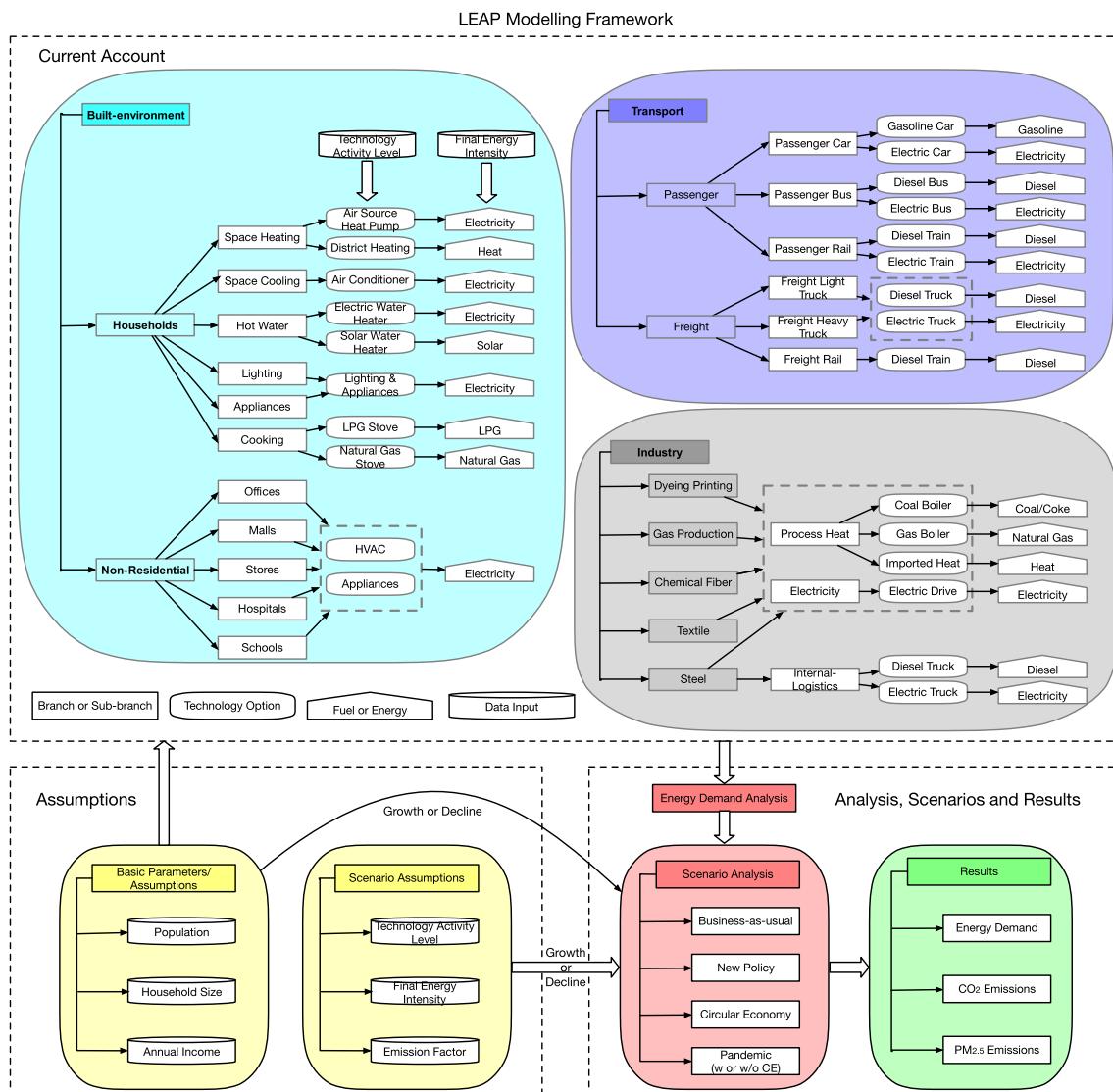


Fig. 3. The LEAP modelling framework.

the impacts of the COVID-19 pandemic. Because the policy measures and the pandemic are likely to affect the growth or decline of the energy activities and the energy technology efficiencies. Inside the LEAP model, the variations of the parameters in different scenarios and the

corresponding references are given in the tables of [Supplementary Material B](#). The reasons for the parameter variations are explained in the following section of [3.2–3.5](#). The LEAP model file is provided in [Supplementary Material C](#).

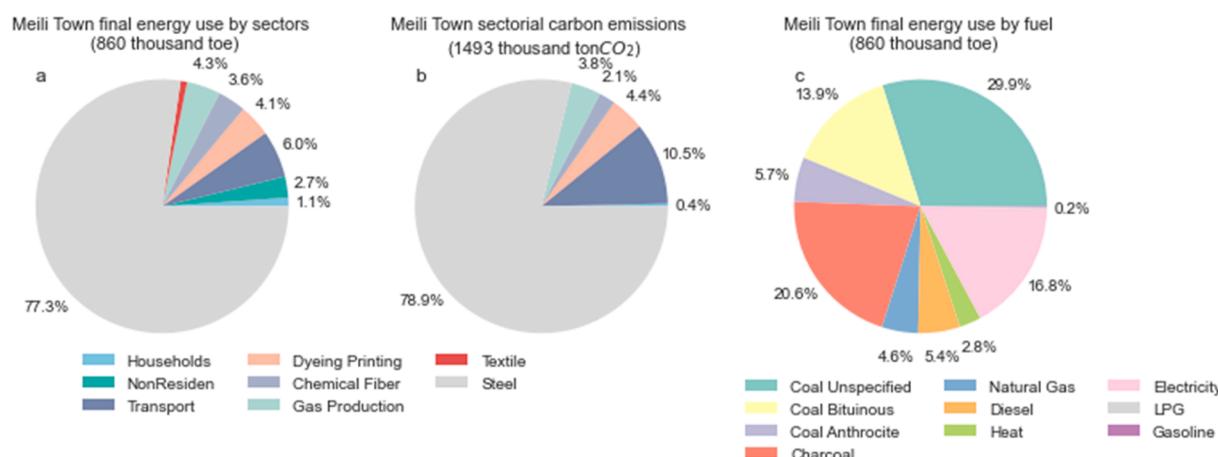


Fig. 4. Meili Town energy system portrayal in 2019: Current Account (data compiled from [8,10,38,40–48]).

### 3.2. Business-as-usual scenario

**Fig. 4** shows Meili Town's current final energy demand by sector (a), current carbon emissions by sectors (b) and final energy use by fuels (c). Meili has an atypical mix of energy demand, whose structure is heavily weighted towards the steel industry and coal. **Fig. 4(a)** shows that the steel industry dominates the energy consumption, which accounts for 77% among the 860 ktoe total final energy use. This is followed by chemical fiber, textile, dyeing-printing and gas production. Residential households, commercial and public buildings and the transport sector only account for less than 10% of final energy use [38]. Correspondingly, the steel industry leads to 79% CO<sub>2</sub> emissions as shown in **Fig. 4(b)**. The transport sector accounts for 11% CO<sub>2</sub> emissions. Therefore, decarbonizing the industry sector and transport sector are the most significant targets for the clean energy transition in Meili [39]. It can be found from **Fig. 4(c)** that coal is the backbone of Meili's industries. Several types of coals are used extensively. Meili's electricity consumption is imported from the national grid.

The business-as-usual scenario projects current energy demand to 2040 based on recent socio-economic activity trends with no new energy efficiency policies implemented.

The residential buildings are either single-family houses or high-rise multi-family apartment buildings. Typical building energy consumption data is provided by Meili government, and checked with other related statistics [49]. The residential buildings do not have a district heating and cooling system [41]. Air-conditioners are installed in individual households for both heating and cooling purposes [50]. Cooking thermal loads are satisfied by liquefied petroleum gas (LPG). Only a small fraction of residential districts use natural gas [45]. For households, the energy demand growth rate is around 1.2% annually. Two significant demand increases are from space heating and domestic hot water supply, which is 20% and 60% respectively. The commercial buildings in Meili include a variety of services such as schools, banks, offices, supermarkets etc., throughout which there are some parks, green lands and sports grounds. The commercial building energy consumption is mainly electricity and is foreseen to grow as the local GDP is transforming from industry into the services sector [51]. Other trends follow China's national policy intentions [52]. The non-residential buildings, on the other hand, experience a higher energy demand growth rate of 2% annually [53]. The current transport sector of Meili has roughly 40,000 vehicles, which consists of cars, buses, trucks. Demand for diesel, used primarily for freight and correlated with industrial activity, grows at 3.6% per year. The passenger vehicle activity has a growth rate of 3.2% annually [54]. The non-ferrous industry in Meili grows at 3.6% per year to 2040. The steel production in Meili reaches a plateau [55]. The attenuation of steel industry (-1.4% per year) leads to a new pattern in energy demand [56].

### 3.3. New policy scenario

The new policy scenario inherits the activity trends from business-as-usual scenario, and considers new energy efficient policies implementation. As Meili's energy supply is heavily skewed towards coal, the local authority is seeking to curb the coal consumption and gradually move away from the reliance on coal. In the new policy scenario, energy demand growth of Meili further slows down to 0.6% per year. For non-ferrous industries, new energy efficient policies will be able to reduce the energy intensity by 3.9% per year [57]. The new Meili industry will gradually transform into high-tech driven smart manufacturing and economic growth shifts to technological innovation, consumer spending and services. Dominance of coal is under challenge from more environmentally benign sources despite still being the major primary energy source. The steel industry will be able to reduce energy intensity by 2.1% per year. For transport sector, by 2030 a quarter of the vehicles in Meili are projected to be electric, and this number further reaches 50% by 2040. This is in-line with the national and international policy

projections [54].

### 3.4. Circular economy scenario

The circular economy scenario inherits the activity trends and new policies from the new policy scenario, with further circular economy measures implemented. This is in line with current national and local policies. China aims to be carbon neutral by 2060 [4]. China is also the world's largest investor and installer of renewable energy, including hydro, wind and solar energy [58]. China's Nationally Determined Contribution NDC aims to peak CO<sub>2</sub> emissions around 2030 or earlier, to reduce CO<sub>2</sub> emissions per unit of GDP by 60% to 65% by 2030 compared to 2005 and to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030 [59]. In addition, China has a Circular Economy Promotion Law in place [60]. All scenarios, including the circular economy scenario, are therefore based on current policy priorities by the Chinese government.

Meili Town has a receptive stance on implementing innovative solutions to achieve its sustainable development goals. Circular economy is a set of promising concepts to level up Meili Town's sustainability. Circular economy extends current business operations to capture the highest economic values that would otherwise be discarded. In the context of energy system, circular economy mainly means cascading use of energy to increase its exergy efficiency by prolonging the business value chains [26]. Several possible circular economy strategies are identified for Meili Town energy system.

The first strategy is cascading use of the behemoth excess heat (1000 °C and higher) produced by the steel industry. Meili industries are working separately at the moment, no synergies are generated. By creating industrial symbiosis through a shared heat network, industries that consume lower grade heat, such the textile industry (100 °C) and the dyeing-printing industry (200 °C), can replace the heat produced from their small coal/gas boilers and avoid importing heat from a remote coal power plant. Also, the steel furnace's surplus heat can be used to provide district heating and domestic hot water supply to its nearby 40,000 Meili households, albeit the heat consumption from households only accounts for a very small share compared with industries. In the circular economy scenario, the process heat demand from less energy-intensive industries and households heat demand are fully covered by the steel industry from 2025.

Electrification of the transport sector is considered as the second prominent circular economy strategy for Meili Town. As the renewable electricity takes more share in the electricity grid, it is beneficiary to power electric vehicles as well as to use electric vehicles to balance the grid [61]. Especially since the dominance of industrial logistics, it is particularly environmental benign to electrify trucks [62]. The batteries of electrified vehicles can be recycled to serve as energy storage for a second life application [63]. In electric vehicles (EVs), the core component is the Lithium-ion Battery (LiB) pack, where individual electrochemical cells are connected to provide power for EV mobility. Usually the manufacturers provide an 8–10 years' warranty to the LiB pack. After that, the batteries are considered inappropriate for road transportation services, even though they could still retain 80% of their original capacities [64]. From a circular economy perspective, it is possible to reuse the LiB for electricity storages in a less demanding environment such as the stationary applications. For example, to balance the grid from the impact of the intermittent wind and solar electricity, or to be used in the renewable electricity charge stations for EVs. For the purpose of energy storages, the LiB is firstly detached from the vehicle, then goes through a state-of-health (SoH) test. The SoH of a LiB is defined as the ratio between its actually capacity and its initial capacity. The SoH of a LiB is often 80% when starting to work as storages. When the SoH of a LiB degrades to around 60%, it is considered to reach its end of life [65].

In the circular economy scenario, the energy model assumes that the circular economy measures will prolong the value chain of the EV

industry. Under new circular economy business models, either the EV owners or the EV manufacturers could recover part of EV purchasing or manufacturing cost by selling the LiB packs to the energy companies who reuse them for electricity storages. This new business model will boost the EV market and will increase the EV penetration rate to 50% in Meili by 2030, and further to 75% by 2040.

Municipal waste-to-energy is a third circular economy strategy. Meili Town produces around 55,000 tons municipal solid wastes in 2020 [66]. However, its contribution to Meili is not considered in the study. Since for the 38.5% waste burned for heat and electricity, the incineration process is carried out outside of Meili, which is beyond the system boundary.

### 3.5. Pandemic scenario

The pandemic scenario inherits the energy efficient measures from new policy scenario. The COVID-19 pandemic is inflicting high uncertainties on international and national activities. Although it is still not possible to completely estimate the impacts of the pandemic, it has definitely reduced the global economic output [67]. Many countries only partially ease the lock-down measures to recover the economy. The International Monetary Fund projected a world economy recession of 3% for 2020 [68].

Meili Town is no exception. Despite there being no specified statistics available at the moment to postulate the industrial production conditions in Meili, it is reasonable to assume some impacts on economic and industrial output [69]. Following lock-down and later on social distancing, Meili's industry experienced a production supply shock during the first months of the COVID-19 outbreak. After aggressive lockdown measures flattened the infection curve, gradual release of socio-economic activities reopened Meili's industries. However, since Meili industries mainly export products to overseas, the recession in the international market as well as the concussion from international politics further exerted a demand shock, which cut 10% of the orders in 2020 [70]. Based on expert projections, this shock is assumed to last for 5 years till 2025. Afterwards, the industrial activities of Meili is projected to recover back to pre-pandemic level and continue with a similar level of annual growth.

The government of China, meanwhile, enacted fiscal efforts to boost industrial productions [71]. National plans and policies are released to gradually establish a domestic economic cycle to partially decouple with the unbalanced reliance on the international market. It is assumed that by 2030 this new domestic cycle can be strengthened. However, it is

uncertain how far decarbonizing actions can still be taken on Meili's industries, because the top priority of the government is to reboot the economy and increase jobs. Yet, nearly a year into the pandemic in China, the government announced the 2060 carbon neutrality goals, hence showing a long-term ambition to decarbonize [4]. This uncertainty is evaluated by assuming: 1 circular economy measures will still be introduced despite the pandemic; 2 no circular economy measures taken due to the pandemic.

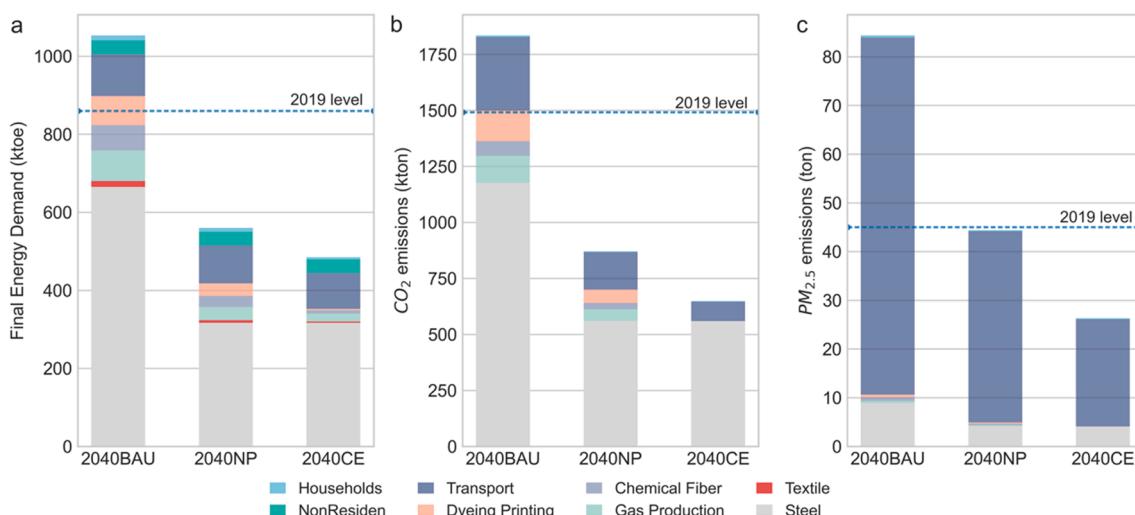
## 4. Results and discussion

The projection results of the scenarios are compared and discussed in this section.

### 4.1. The outcomes from the circular economy

In general, the new policy scenario reflects a more efficient and sustainable energy system, provided that Meili implements energy policies in accordance with national targets. However, with the momentum given by circular economy, Meili could achieve an even better alternative. For the situation in fiscal year 2040, as shown in Fig. 5(a), new policies can reduce final energy demand by 47% compared with business-as-usual. However, introducing circular economy measures could further enhance the reduction by 7%. A similar trend can be observed for CO<sub>2</sub> emission from Fig. 5(b), where a circular economy energy system could help avoid 65% CO<sub>2</sub> emissions by 2040 compared with 53% in new policy scenario during the same year.

Interestingly, implementing only new energy efficient technologies in the new policy scenario could merely enable Meili to curb the menace of air pollution. Fig. 5(c) shows that despite the new policy scenario could reduce PM<sub>2.5</sub> emissions by 47% in 2040 compared with business-as-usual, its emission level is nearly the same as 2019 level. It means the new policy actually does not improve the air-quality, only keeps it from getting worse. Although the technology efficiency improves overtime (both electric vehicle penetration and cleaner combustion engine contribute to that), the fast increase in transport demand actually leads to a rebound effect. Circular economy, on the other hand, could greatly improve air quality by pushing the electrification of the transport sector to a deeper level. Batteries-for-second-life makes electric vehicles more profitable and could level up the market share to 75% by 2040. Hence, circular economy could help further reduce PM<sub>2.5</sub> emission by 22% in 2040.



**Fig. 5.** Comparisons between business-as-usual (2040BAU), new policy scenario (2040NP) and circular economy scenario (2040CE) in Final Energy Demand (a), CO<sub>2</sub> emissions (b) and PM<sub>2.5</sub> emissions (c).

#### 4.2. The impacts by the COVID-19 pandemic

The COVID-19 pandemic brought international commerce to a standstill. A sudden cessation of normal activities, especially in industries, significantly incurred to the attenuation of energy demand and associated emissions.

It is shown in Fig. 6(a) and (b) that the long-term effects from the COVID-19 pandemic and associated international politics instability significantly reduces Meili's industrial energy activities and associated CO<sub>2</sub> emissions. However, the inflection point occurs when the COVID-19 pandemic fades at around 2024. If Meili then goes back to the pre-pandemic development route (the new policy scenario) with the intention to quickly boost the economy, the final energy demand and CO<sub>2</sub> emissions will level up. By 2040, the final energy demand and CO<sub>2</sub> emissions (red lines) will surpass the circular economy scenario (green lines). But if taking the pandemic as an opportunity to further accelerate sustainable energy transition using circular economy, the outcomes will be the best among all scenarios (purple lines) at post-pandemic era. For pandemic scenario with circular economy, the total accumulated final energy saving from 2020 to 2040 could be 9.1 Mtoe, 8% more than the saving from pandemic scenario without circular economy strategies (7.5 Mtoe). The associated accumulated CO<sub>2</sub> emissions saving from 2020 to 2040 could be 17.6 Mt for the pandemic-with-circular-economy scenario, 11% more than the saving from the pandemic-without-circular-economy (13.8 Mt).

For PM<sub>2.5</sub> emissions, the rebound effect is clearly shown in Fig. 6(c) for non-circular economy scenarios. Even the pandemic causes a drop of PM<sub>2.5</sub> emissions due to restricted transportation usage at the beginning (red line), it quickly rebounds and peaks at around 2035. Only by implementing circular economy measures can Meili cap the air pollutants emissions.

The explanation of the rebound effect is as following: The PM<sub>2.5</sub> emissions are mostly attributed to the gasoline and diesel consumption from the transport sector. Its total emissions are dependent on both the transportation activity levels and the vehicles' fuel/energy efficiency. In all scenarios, the transportation activity grows faster than the combustion engine fuel efficiency improvements. The two driving variables counteract with each other. Only with the electrification of the transport sector could the energy efficiency improvements offset the deterioration of the environmental pollution brought by the transportation demand growth, as an electric vehicle is much cleaner than a combustion engine vehicle. In non-circular economy scenarios, by 2035 the share of the electric vehicle reaches around 35% of the total vehicle, and the PM<sub>2.5</sub> emissions peaks at this stage. Circular economy, on the other hand,

could significantly accelerate the electrification of the transport sector (50% by 2030) as it introduces recycling, remanufacturing and reuse of the vehicle batteries for a second life in energy storages, which prolongs the products' value chain and establishes new business model. This effect quickly mitigates the PM<sub>2.5</sub> emissions from combustion engine vehicles and prevents the rebounds from happening.

As could be noticed, the rebound does not occur for the CO<sub>2</sub> emissions. Because in Meili Town the CO<sub>2</sub> emissions and PM<sub>2.5</sub> emissions are decoupled. The CO<sub>2</sub> emissions are mainly attributed to the coal and gas consumption from industrial activities, especially the steel industry, while the PM<sub>2.5</sub> emissions are mainly from the transport sector. For CO<sub>2</sub> emissions, with the implementation of new policies, the steel industry activity could be attenuated and the technology efficiency improves for all industries. As both variables of activity level and final energy intensity contribute to the decarbonization, the rebound effect does not occur. For the energy demand, the main consumption sector is the industry. There, the energy efficiency improves significantly both by cascading heat use and technology efficiency improvements. The energy activities increase mildly for non-steel industries and attenuate for steel industry. Therefore, the total combined effect does not result in a rebound.

#### 5. The clean energy transition and sectorial contributions

Fig. 7 illustrates how much each sector can potentially contribute to Meili's clean energy transition, when comparing the circular economy scenario with the business-as-usual scenario. The belt width is proportioned by the logarithms of the absolute savings from each sector, in order to have a better visualization. The industrial sector plays a leading role in final energy saving and decarbonization. The transport sector contributes the most to PM<sub>2.5</sub> mitigation.

Meili Town's industrial sector consumes energy and emits CO<sub>2</sub> at 10 times the rate of the transport and building sectors, dominated by the steelworks. Its total contributions are among the top in all three indicators. Replacing the unsustainable heat consumption in non-ferrous industries using circular economy measures can contribute greatly to energy saving and CO<sub>2</sub> emissions saving (see dyeing-printing, chemical fiber and gas production). Electrification of transport sector contributes significantly to CO<sub>2</sub> saving and PM<sub>2.5</sub> saving. Decarbonizing the steelworks is challenging and therefore should be the focus of technology and system innovation. While the focus in China's steel industry is mainly on energy efficiency measures, other countries in Europe are in the R&D stages for fossil-free steel, for example a pilot project in Sweden that tests direct reduction of iron ore from hydrogen [23]. However, such

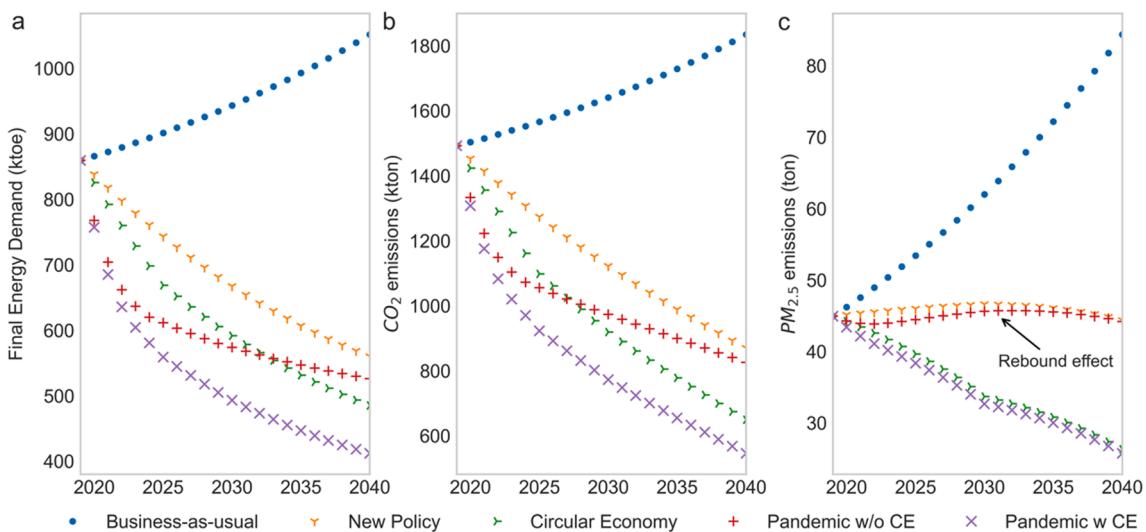
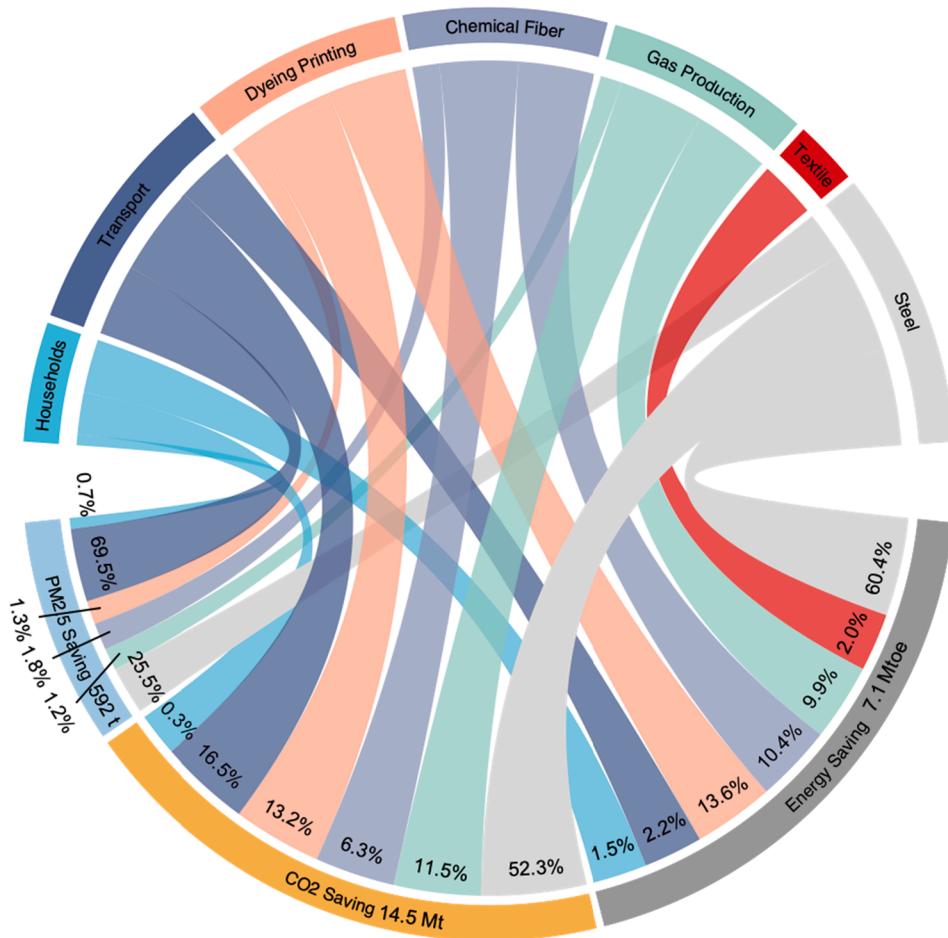


Fig. 6. Development trend of all scenarios in Final Energy Demand (a), CO<sub>2</sub> emissions (b) and PM<sub>2.5</sub> emissions (c).



**Fig. 7.** Sectorial contributions to Meili clean energy system transition.

technologies only make sense in a low-carbon energy system, such as in Sweden, where electricity generation is almost completely based on hydropower, nuclear energy, biofuels and wind energy.

Cascading use heat and electrification of transport sector are two most effective measures, since they can reuse a great amount of energy that would otherwise being wasted, and electric vehicles are more efficient than combustion engine vehicles.

Municipal waste to energy is not effective since the energy recovered is too trivial compared with industries and transport sector. Also, since the incineration plant is outside Meili's energy system boundary and the generated electricity is exported to the grid, it is arguable to allocate the benefits to Meili as the electricity is not consumed locally.

## 6. Conclusions

This study analyses the clean energy transition options and corresponding outcomes for a 140,000-population town, named Meili, in East China for the fixed period from 2020 to 2040. The scenarios reflect a technically feasible range of options with different fossil fuel consumption, carbon dioxide and air quality related emissions. Four scenarios are developed, which consider industrial, transport and building consumers and the changes in the patterns of their consumptions over time. These scenarios are in line with China's current policy ambitions to peak its emissions by 2030, become net zero emitters by 2060, increase its share of renewable energy and reduce its energy and carbon intensity.

The results indicate that circular economy options, represented by cascading use of industrial surplus heat and electrification of the transport sector, have great potential to facilitate Meili Town's clean energy system transition. By implementing circular economy measures,

the improved savings in accumulated (2020–2040) final energy use, CO<sub>2</sub> emissions, and PM<sub>2.5</sub> emissions could be 7%, 10% and 17% respectively, compared with the new policy scenario which simply implements energy efficiency measures.

The COVID-19 pandemic exerts uncertainties on the transition of Meili's sustainable energy system. But it is also a new opportunity to accelerate the clean energy transition by implementing circular economy approaches. It is estimated that with circular economy strategies, during 2020–2040, Meili could save 8% more accumulated final energy use and it could save 11% more accumulated CO<sub>2</sub> emissions compared with the non-circular economy scenario during post-pandemic times. Only with the implementation of circular economy measures can the energy system diminish the rebound effect in total PM<sub>2.5</sub> emissions. These results can be useful for policy-makers and researchers as a roadmap for decarbonising Meili Town; as well as for better understanding the role of energy and emissions in the circular economy.

## CRediT authorship contribution statement

**Chang Su:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision. **Frauke Urban:** Writing - original draft, Writing - review & editing, Validation.

## 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.

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apenergy.2021.116666>.

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