Chapter 7
Local Low-Carbon Society Scenarios of Urban-Rural Linkage

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Abstract In order to realize a low-carbon society, the introduction of low-carbon energy resources in the local (both urban and rural) energy systems, which plays a main role in the total CO_2 emissions, is being paid more and more attention. In this chapter, the paths toward regional de-carbonization are indicated by conceptualizing systematic "urban-rural cooperation" that creates regional circulation of energy resources (e.g., biomass). As an illustrative example, an investigation has been conducted of assumed distributed energy systems for the Huzhou City, which is an environmental model city in China. By extending a pre-developed plan and evaluation model to include not only cost minimization but also emissions minimization, the proposed wide urban-rural energy systems are examined from both economic and environmental viewpoints. According to the simulation results, the energy system with urban-rural mutual cooperation is the best option from both economic and environmental viewpoints, and it results in a cost-effective reduction of CO_2 emissions up to 50% of current level. In addition, by endowing an economic value to the reduced CO_2 emissions through a local carbon price, the economic and environmental merits for urban and rural areas can be shared and balanced between both sides.

7.1 Research Objective and Energy Demands

In this chapter, Huzhou City, which has been declared a model environmental city by the Chinese government, is used as a case study to examine the effectiveness of local energy management based on urban-rural cooperation. According to local statistics, total electricity demand is approximately 9.6 billion kWh (4.2 billion kWh for urban

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and 5.4 billion kWh for rural areas), and thermal requirements are approximately 24.5 billion MJ (12.6 billion MJ for urban and 11.9 billion MJ for rural areas). Figures 7.1 and 7.2 illustrate monthly and hourly electricity consumption, respectively.
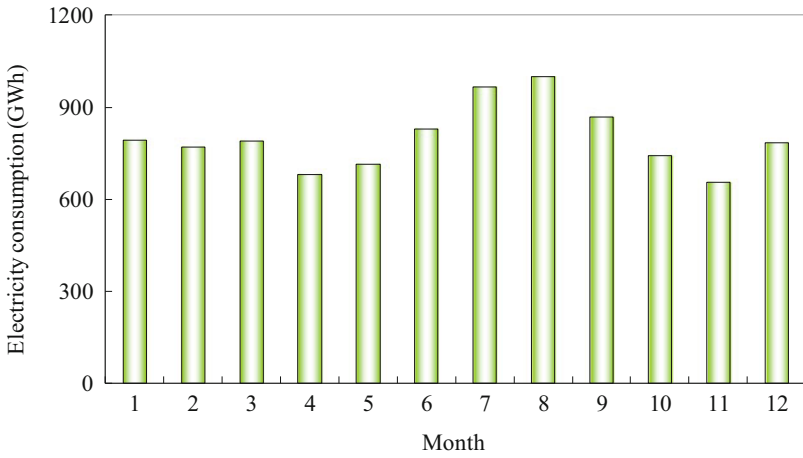

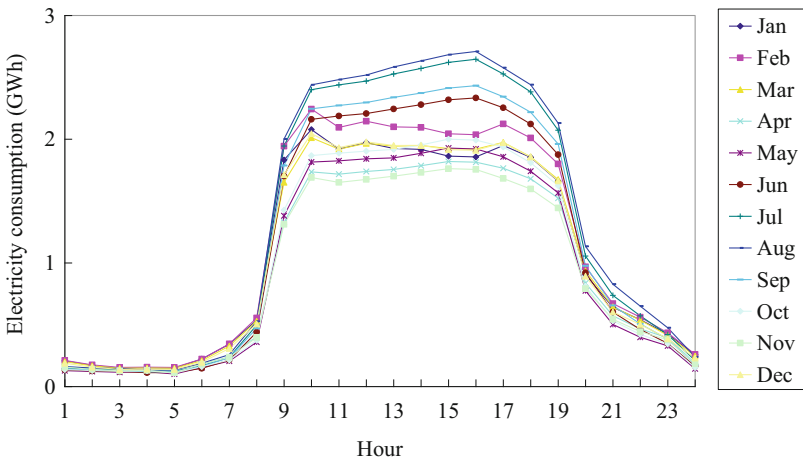**Fig. 7.1** Monthly electricity consumption in Huzhou City

Fig. 7.2 Hourly electricity consumption in Huzhou City

7.2 Local Renewable Energy Stocks

As Huzhou City has a relatively low urbanization ratio, biomass is expected to be the main renewable energy resource in the local area. Figure 7.3 shows the annual distribution of available biomass energy stocks in urban and rural areas. Generally, agricultural biomass is the main biomass resource, followed by woody biomass, food biomass, sewage sludge, and livestock biomass. Biomass energy stocks in rural areas are about twice those in urban areas. Therefore, in order to make full use of local natural resources, rural biomass resources should be adequately considered.

Solar energy is another key local renewable energy resource that can contribute to low-carbon energy systems to a great extent. Figure 7.4 illustrates the monthly cumulative radiation and average temperature in the local area. Solar radiation is not consistent with average temperature. In July and August when the temperature is highest, monthly cumulative radiation is relatively low compared with, for example, May.

7.3 Local Energy System Scenarios

In order to understand the effect of dominance by particular areas of the city on formation of a local energy system based on urban-rural cooperation, three scenarios with different system structures are explored, plus a baseline scenario without cooperation for comparison. On the supply side, various technologies have been assumed; on the demand side, electricity and heat are the two main energy forms consumed in both urban and rural areas. The scenarios are described below (Ren et al. 2014):
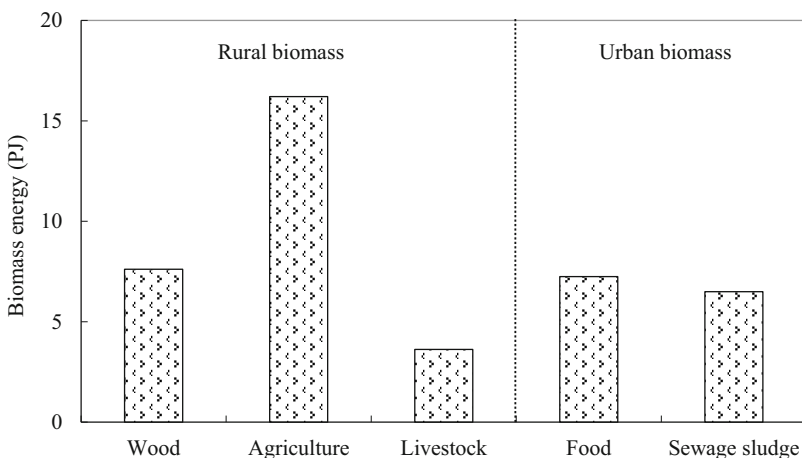

Fig. 7.3 Biomass energy reserves in urban and rural areas of Huzhou City
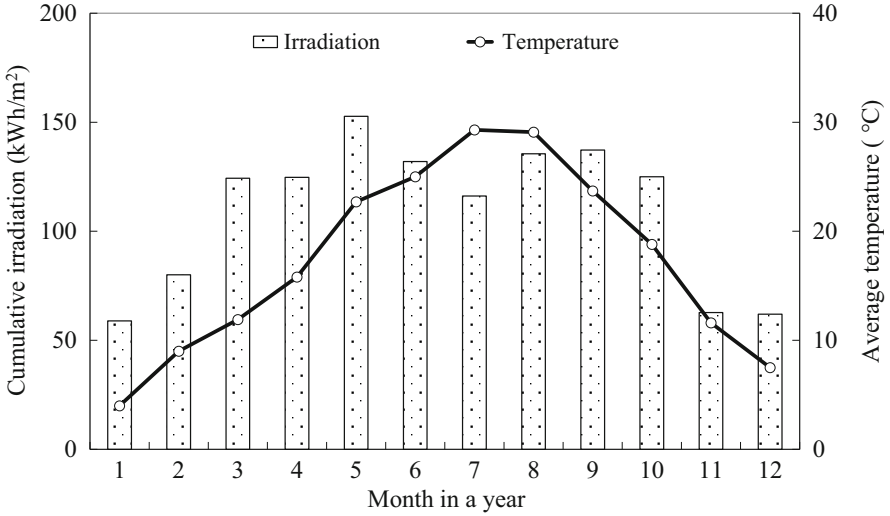
Fig. 7.4 Monthly cumulative irradiation and average temperature in Huzhou City
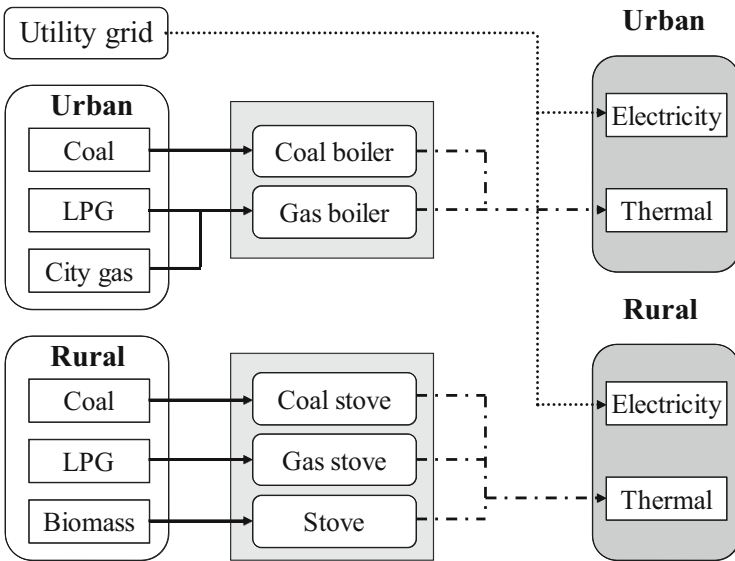

Fig. 7.5 Energy flow of Scenario 0 (no cooperation)

Scenario 0: No cooperation

In this scenario (Fig. 7.5), electricity demand in both urban and rural areas is supplied by the utility grid, generated mainly by fossil fuel combustion. Thermal requirements in urban areas are served by boilers fueled with coal, liquid
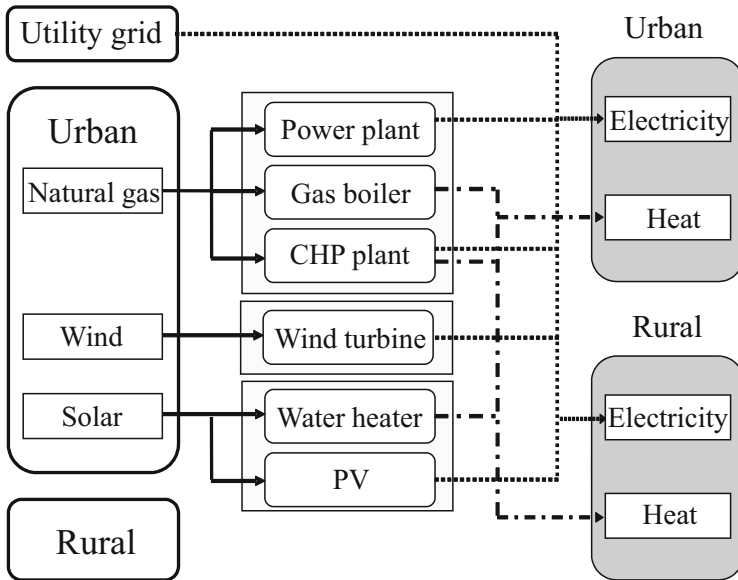
Fig. 7.6 Energy flow of Scenario 1 (urban dominant cooperation)

petroleum gas (LPG), or city gas. In contrast, conventional noncommercial biomass takes the main role in fulfilling thermal requirements in rural areas. Deficiencies are supplemented by coal or LPG-fueled stoves.

Scenario 1: Urban dominant cooperation

In this scenario (Fig. 7.6), urban areas play the main role in serving energy demands in the local area (covering both urban and rural areas). Natural gas, which is a relatively clean fossil fuel, is utilized for power generation, thermal supply, or a combination of both via combined heat and power (CHP) plants. Solar energy is also considered for both electricity and heat generation. If local power generation cannot satisfy total electricity demand, the utility grid can be used when necessary. This scenario is considered appropriate for cities with a relatively high rate of urbanization.

Scenario 2: Rural dominant cooperation

In this scenario (Fig. 7.7), rural areas are considered energy centers, through exhaustion of local natural resources. In addition to solar energy, rural biomass takes a dominant role in this scenario in order to satisfy both electrical and thermal requirements. Micro wind turbines and hydropower may also be available depending on local conditions. The utility grid and heat pumps are employed to service residual electrical and thermal demands, respectively. This scenario is anticipated to be appropriate for cities composed mainly of rural areas.
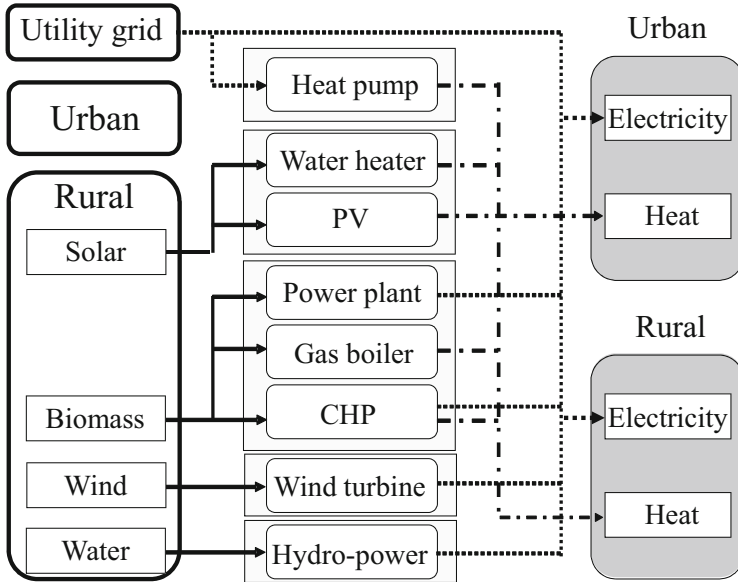
Fig. 7.7 Energy flow of Scenario 2 (rural dominant cooperation)

Scenario 3: Urban-rural mutual cooperation

In this scenario (Fig. 7.8), both urban and rural areas take an equal role in the local energy system. Natural resources in the local area are expected to be fully exploited as the main energy carrier to serve local energy requirements. Nevertheless, in order to guarantee consistent energy service, connection to local utilities remains necessary.

7.4 Energy Technology Options

As important input data for a bottom-up optimization model, technical information regarding both electricity and heat generation are assumed according to previous studies, as shown in Table 7.1 (Kojima et al. 2007; Nagata 2009; NEDO 2010; Ruan et al., 2009; Xu, 2008). Wind power and hydropower are not included in the following analysis due to local topographic conditions.
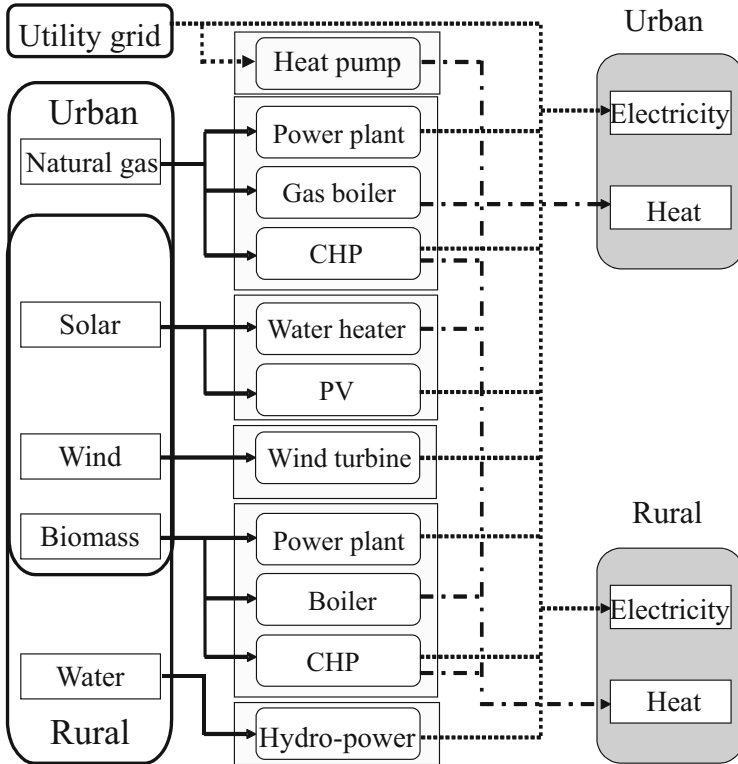
Fig. 7.8 Energy flow of Scenario 3 (urban-rural equal cooperation)

7.5   Optimal System Combination

Optimal system combination is an important part of designing a local energy system. For all three scenarios, the option with the lowest CO_2 emissions has greater total power generation capacity and smaller heat generation capacity than the option with lowest total cost (Fig. 7.9). This is because CO_2 emissions are minimized with widely used CHP technology, which leads to reduced thermal requirements from additional heat sources. In addition, when economic objectives are considered, most electricity requirements can be served by the utility grid, and thermal load is mainly supplied by solar heating supplemented by natural gas or biomass boilers. When environmental objectives are optimized, different scenarios have different optimal system combinations. For Scenario 1, a fuel cell system (PA) and natural gas power plant (NP) are the main options, with capacities of 1.9 GW and 0.7 GW, respectively. In Scenario 2, solar photovoltaic (PV) becomes dominant, followed by some biomass power generation. When urban and rural areas are coupled in a bilateral way (Scenario 3), all electrical and thermal demands can be satisfied by local generation,

Table 7.1 Cost and efficiency of technologies examined in this chapter

Fuel	Technology Index	Equipment	Capital cost ($/kW)	Efficiency (%) Electricity	Heat
Coal	CB	Boiler	89	–	70
LPG	LB	Boiler	111	–	80
	LS	Stove	22	–	40
Electricity	HP	Heat pump	5556	–	3
Natural gas	NB	Boiler	111	–	90
	NP	Power plant	1778	48	–
	DE	Diesel engine	2444	38	16
	PA	Phosphoric acid fuel cell	7778	40	40
	GE	Gas engine	2778	30	40
	GT	Gas turbine	2222	23	51
Solar	SH	Heater	222	–	30
	PV	PV	6667	14	–
Woody biomass	WF	Direct fired	5333	28	–
	WG	Gasification	7778	36	–
	WA	Boiler	1111	–	65
	WC	CHP	11,111	23	43
Agricultural biomass	AF	Direct fired	3889	18	–
	AG	Gasification	5556	25	–
	AB	Boiler	889	–	50
	AC	CHP	7444	20	40
Livestock biomass	LA	Anaerobic digestion	7556	25	–
	LG	Gasification	5556	22	–
	LB	Boiler	1667	–	55
	LC	CHP	13,333	25	45
Food biomass	FG	Gasification	7778	18	–
	FA	Anaerobic digestion	11,111	25	–
	FB	Boiler	2222	–	50
	FC	CHP	16,667	25	45
Sewage sludge	SF	Direct fired	8889	21	–
	SA	Anaerobic digestion	12,222	25	–
	SB	Boiler	1667	–	55
	SC	CHP	17,778	21	40

of which PV has the greatest capacity of approximately 2.3 GW, followed by biomass CHP systems.

Thus, although PV systems and biomass CHP plants result in reasonable environmental benefits, they are unpopular economically due to relatively high initial costs. As buffering options, solar heaters and heat pumps, as well as natural gas-fired power plants and CHP systems, can be introduced to reduce CO_2 emissions with acceptable costs over a short-term period.
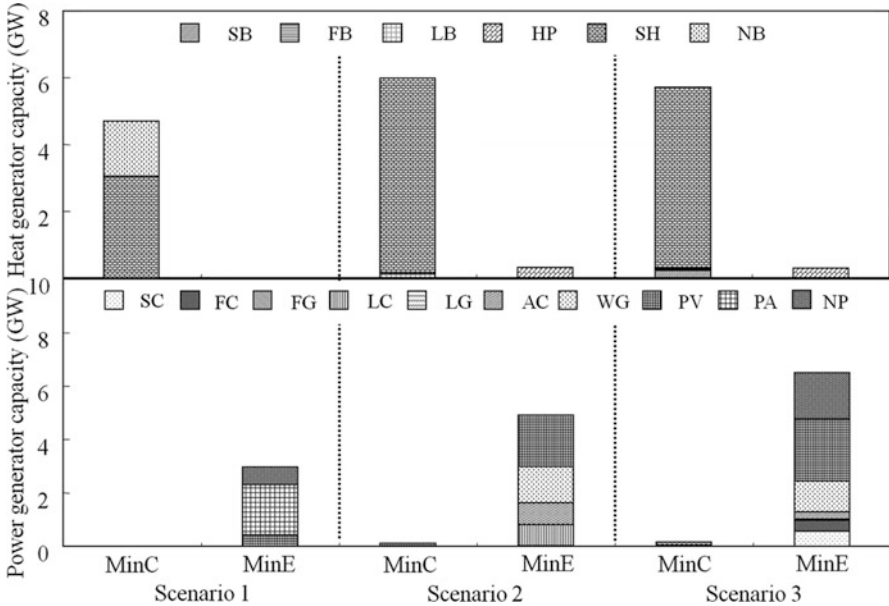
Fig. 7.9 Power and thermal generation capacity for various scenarios from economic and environmental perspectives

7.6   Economic and Environmental Performance

Simulated economic and environmental performance of different cooperative patterns in various scenarios is shown in Table 7.2. When total cost is minimized, Scenarios 2 and 3 both result in simultaneous reduction of cost and CO_2 emissions. In Scenario 1 (urban dominant cooperation), the emissions reduction ratio is relatively low and the total cost increases by 1.3% (compared with Scenario 0). When the environmental objective is minimized, annual energy costs dramatically increase, although CO_2 emissions are reduced to relatively low levels in all three scenarios. Scenario 1 has better economic and environmental performance than Scenario 2, in contrast to the situation with minimum cost. Therefore, natural gas is a good option to reduce CO_2 emissions, especially when utilized in a CHP system. In addition, from either an economic or environmental viewpoint, Scenario 3 (urban-rural mutual cooperation) is recognized as the best alternative with the lowest energy cost (economic objective) and CO_2 emissions (environmental objective).

Table 7.2 Economic and environmental performance of various scenarios

Scenario	Total cost (million USD)	Total CO_2 emissions (million ton)	Cost reduction ratio (%)	Emissions reduction ratio (%)
Total cost minimization (MinC)				
Scenario 1	1201	10.2	−1.3	7.2
Scenario 2	1044	8.4	11.9	24.0
Scenario 3	1036	7.9	12.6	28.5
CO_2 emissions minimization (MinE)				
Scenario 1	2232	4.1	−88.4	62.6
Scenario 2	3209	5.5	−170.8	50.1
Scenario 3	3564	1.6	−200.8	85.1

7.7 Influence of CO_2 Emission Constraints on System Combination

In the following analysis, while constraining annual CO_2 emissions to a 10–50% reduction, system combinations are analyzed with annual total cost as the objective function to be minimized. For Scenario 1, as the emissions reduction ratio increases, the share of energy from the utility grid gradually decreases, and natural gas becomes the dominant energy carrier (Fig. 7.10). In addition, solar heat is introduced with a constant value, which results in steady total energy supply. The emissions reduction cost increases from 0.023 USD/kg CO_2 to 0.058 USD/kg CO_2 when CO_2 emissions are reduced to half their current value.

In Scenario 2, as in Scenario 1, the power share from the utility grid gradually decreases as the emissions reduction ratio increases (Fig. 7.11). Solar energy is introduced, and the application pattern gradually changes from solar heat to solar power. Therefore, the PV system has better environmental performance than the solar heater. Rural biomass is also widely used in this scenario. Interestingly, total energy consumption increases sharply as the emissions reduction ratio increases from 10 to 20% and then decreases gradually. The system has a negative reduction cost unless CO_2 emissions are reduced to less than 35% of their current value; economic and environmental benefits can be achieved simultaneously. However, once total emissions are reduced by half, the reduction cost increases to as much as 0.08 USD/kg CO_2.

Scenario 3 is the best option in terms of cost-effectiveness in reducing CO_2 emissions because of its negative reduction cost even when annual CO_2 emissions are halved (Fig. 7.12). Solar power is not adopted in this scenario; as an alternative, biomass energy in both urban and rural areas is exhausted. Natural gas accounts for a
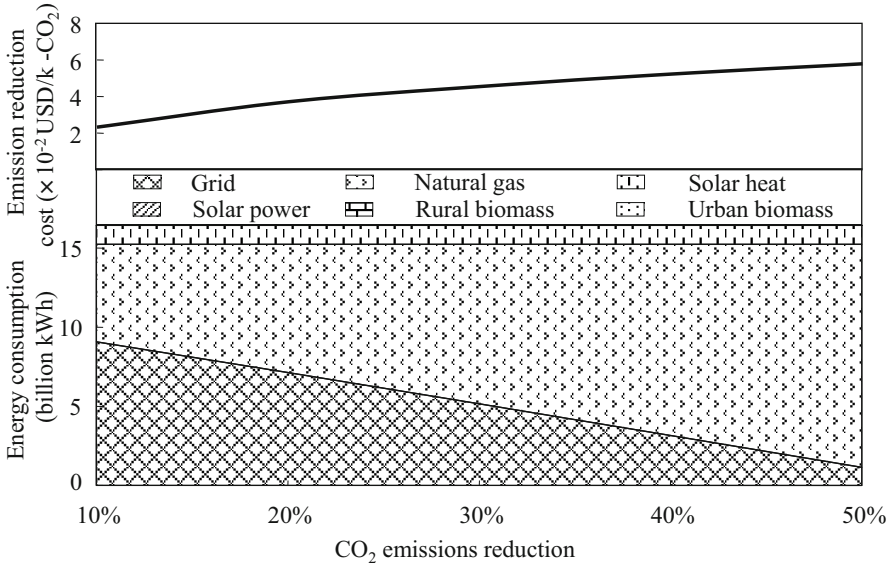
Fig. 7.10 Energy share with various CO_2 emissions reduction ratios and corresponding reduction costs (Scenario 1)
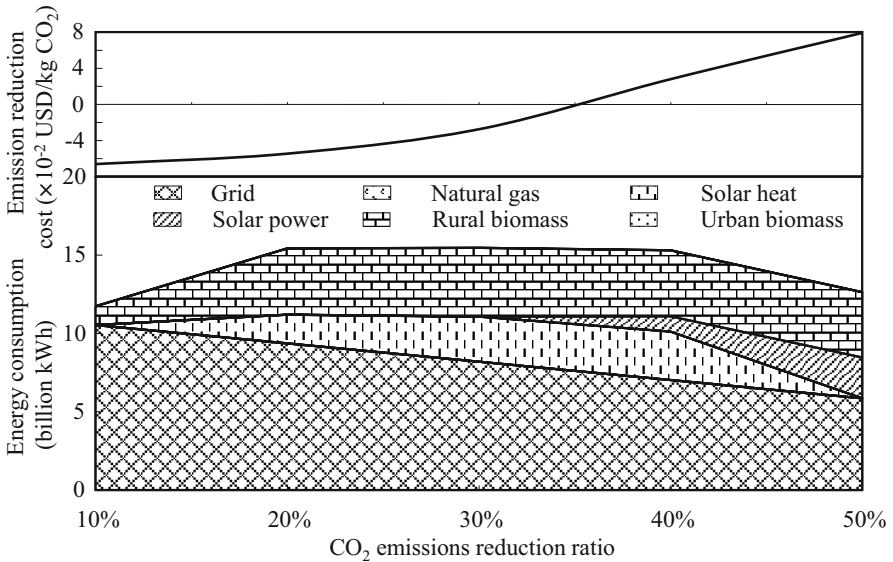

Fig. 7.11 Energy share with various CO_2 emissions reduction ratios and corresponding reduction costs (Scenario 2)
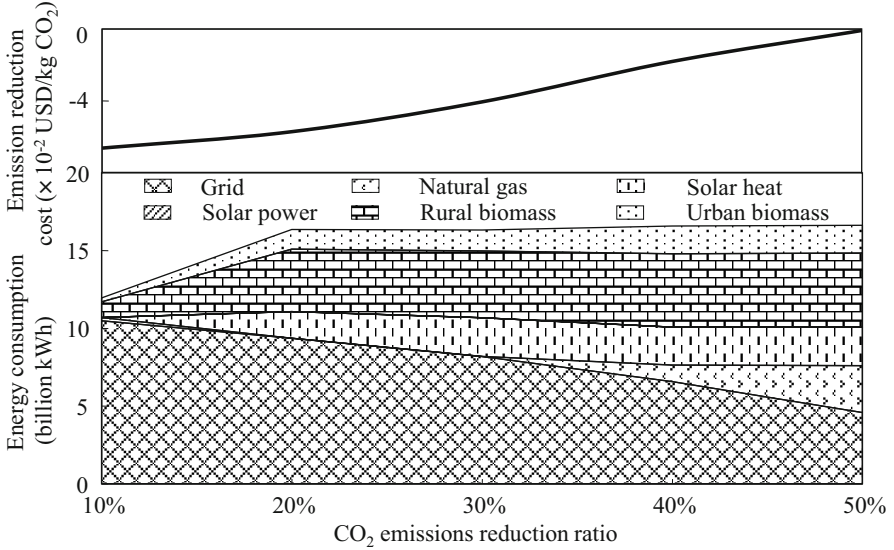
Fig. 7.12 Energy share with various CO_2 emissions reduction ratios and corresponding reduction costs (Scenario 3)

small share of total energy consumption as the reduction ratio is over 30%. Furthermore, similar to Scenario 2, a sharp increase in energy consumption appears when CO_2 emissions are reduced by 20%. This implies that CO_2 emissions and energy consumption do not have a definite linear relationship. This is because although some renewable technologies have no emissions, their efficiencies are relatively low.

7.8 Bridging the Gap Between Urban and Rural Areas

Scenario 3 is considered the best of the three options. In this section, based on the assumption illustrated in Scenario 3, the economic and environmental benefits arising from the introduction of local energy systems are reallocated and balanced between urban and rural areas. This is based on the equality of rights of urban and rural citizens to pay the same energy price and emit the same volume of CO_2. In order to realize this concept, a local carbon price should be assumed, which is employed to transfer money and emission rights between urban and rural areas (Eq. 7.1).

$$C_p = \frac{|C_u - c \cdot \mathrm{PE}_u|}{|E_u - e \cdot P_u|} = \frac{|C_r - c \cdot \mathrm{PE}_r|}{|E_r - e \cdot P_r|} \tag{7.1}$$
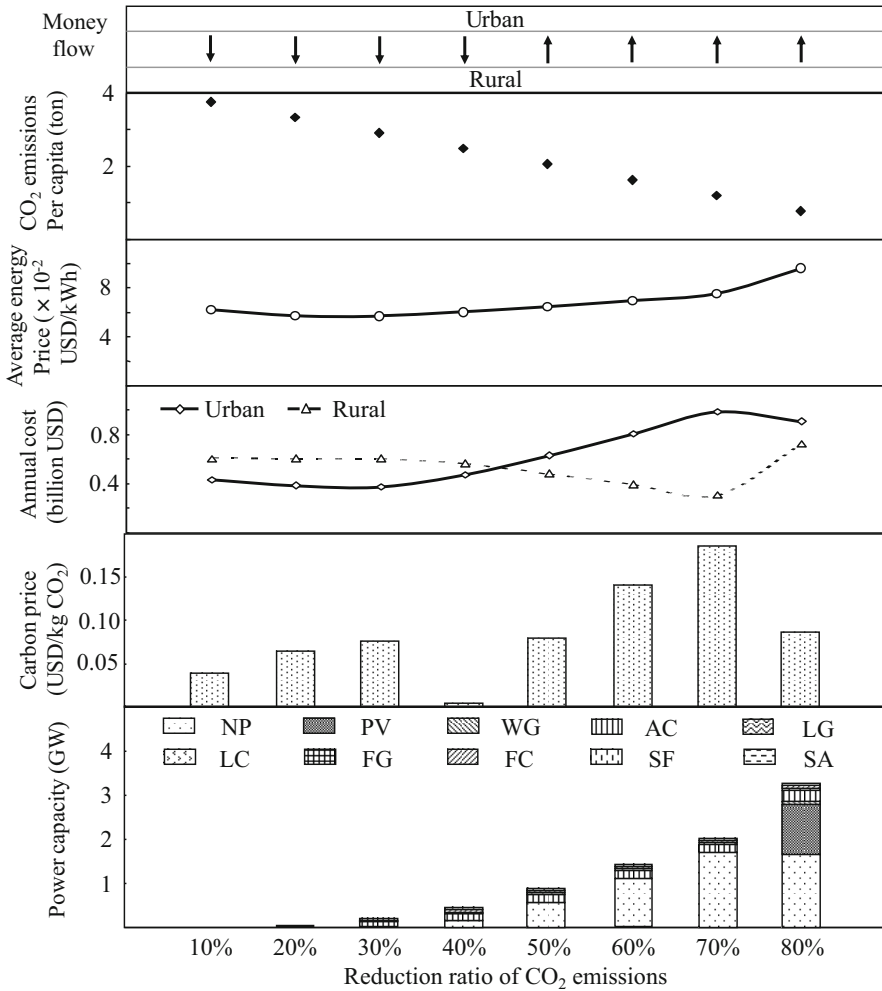
Fig. 7.13 Balance of economic and environmental performance between urban and rural areas

where C_p is the local carbon price, PE denotes annual primary energy consumption, and P is the population. Urban and rural areas are indicated by u and r, respectively, while c and e are the mean energy price and CO_2 emissions per capita, respectively.

Based on this, Fig. 7.13 shows the economic and environmental performance in both urban and rural areas under different reduction targets. Average energy price decreases with decreasing CO_2 emissions, reaching a minimum when the reduction ratio is approximately 30%, after which it gradually increases. When the reduction ratio is relatively low, rural areas have higher energy costs; conversely, the cost in urban areas is higher with larger reduction ratios.

A balanced local carbon price does not illustrate a clear relationship with the reduction ratio. When CO_2 emissions are reduced by 40%, a relatively low carbon price of 0.01 USD/kg CO_2 is sufficient to balance bilateral benefits. Local generation capacity also increases gradually. The PV system is not employed, and natural gas power plants are the dominant option until the reduction ratio approaches 80%.

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