Increase of Residential Electricity Consumption in Urban and Rural China by province

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1. Introduction: REC in China

The Residential Electricity Consumption (REC) in China has been increasing rapidly in response to recent economic growth. According to the *China Energy Statistical Yearbook*, total REC has increased from 48.1 [TWh/y] in 1990 to 223.8 [TWh/y] in 2003. Despite the current high growth, REC per capita in China is still very low compared to the industrialized world; for instance, the current per capital REC consumption level is about one-tenth of that in Japan. Thus, it strongly suggests that future REC growth in China is inevitable, and that the expected increase may cause various adverse environmental impacts, because the Chinese power generation has been dependent on coal. In the present study, we projected REC in China for 1990-2020.

A growing body of literatures has dealt with issues concerning REC in China. Hirshchhause and Adres (2000) have analyzed the relationship between GDP and REC. Lu (2006) has evaluated the effect of improving energy-efficiency of refrigerators. Zhang and Asano (2003) have investigated whether temperature can explain REC. However none of these studies have well-considered the income gap in China. It is widely known that while coastal provinces enjoy benefits of the recent economic reform, inland provinces still face economic stagnation. In addition, intra-provincial income gaps are also large between urban and rural areas. In order to achieve more accurate understanding of REC in China, we must take into account these income gaps. So, we estimated REC by province and also for urban and rural categories.

2. The Model Outline

Fig.1 shows the general scheme of the model. The model has three major sections: In household number section, we developed a population cohort model to estimate the number of household. In appliance penetration section, future penetrations of refrigerators, color-TVs and Air conditioners for cooling were estimated, using income as an exogenous variable. We specifically

focused on these three appliances, because they currently consume a large proportion of REC in China. In electricity consumption section, the numbers of these appliances were calculated by multiplying the number of household and penetration. Finally, we predicted REC of these appliances considering energy-efficiency. Details of each estimation are as follows.

2.1 Household Number

Equations (1)-(4) estimate the future populations of each cohort; i.e. 5-year age groups divided by province, and also by urban and rural area of each province. Each equation estimates the populations aged 0-4, 5-79, 80-99 and 100-, respectively. Likewise, equations (5)-(7) estimate future household numbers for each cohort. These equations estimate the households headed by population aged 0-14, 15-64, and over 65, respectively.

The statistics on population, death rate, birth rate, migration rate, household-owner-rate (HOR) were obtained from the *2000 Population Census, China Population Statistical Yearbook (CPSY) and 1995 1% sample investigation.* When data quality appeared questionable, we have made some adjustments using Zhang (2003) and Wakabayashi (2005). The assumptions used in this study are as follows. The death rate and birth rate were assumed to be constant at the 2000 level. The migration origin, destination and rate were set constant at the 1995-2000 patterns. In this calculation, it is important to accurately predict HOR. However, the Chinese HOR data are available only on a national level. HOR data including urban and rural distinction have not been published since 1994. Therefore, we estimated future and past HOR for urban and rural areas of each province, based on the 1994 national urban and rural HOR. HOR from 1990 to 2020 was set constant. For, the difference in urban and rural HOR is large in 1994, whereas the 2003 national HOR has been relatively constant from 1991.

t : year k : 5-year age group

i, j : urban-rural areas by province

（$i, j = 1,2,\cdots,62 \equiv$ urban Beijing, rural Beijing, …, urban Xinjiang, rural Xinjiang）

m : male f : female

$p^{m}_{t,i,k}$: male population in i for cohort k at year t

$b_{i,k}$: birth rate in i for cohort k s^{m}_{i} : sex of baby in i

$d^{m}_{i,k}$: male survival rate in i for cohort k

$o^{m}_{i,j,k}$: male migration rate from j to i for cohort k

$N_{t,i,0-14}$: household number owned by people aged 0-14 in i at year t

$N_{t,i,15-64}$: household number owend by people aged 15-64 in i at year t

$N_{t,i,65-}$: household number owned by people aged over 65 in i at year t

$h^{m}_{i,0-14}$: male HOR by people aged 0-14 in i

$h^{m}_{i,k}$: male HOR in i for cohort k

$h^{m}_{i,65-}$: male HOR by people aged over 65 in i

$$p^{m}_{t+5,i,0-4} = \sum_{k=15-19}^{45-49} p^{f}_{t,i,k} \times d^{f}_{i,k} \times b_{i,k} \times s^{m}_{i} \ , p^{f}_{t+5,i,0-4} = \sum_{k=15-19}^{45-49} p^{f}_{t,i,k} \times d^{f}_{i,k} \times b_{i,k} \times s^{f}_{i} \quad (1)$$

$$p^{m}_{t+5,i,k} = p^{m}_{t,i,k-1} \times d^{m}_{i,k-1} + \sum_{j=1}^{62} \left(p^{m}_{t,j,k-1} \times d^{m}_{j,k-1} \times o^{m}_{j,i,k-1} - p^{m}_{t,i,k-1} \times d^{m}_{i,k-1} \times o^{m}_{i,j,k-1} \right)$$
$$, p^{f}_{t+5,i,k} = p^{f}_{t,i,k-1} \times d^{f}_{i,k-1} + \sum_{j=1}^{62} \left(p^{f}_{t,j,k-1} \times d^{f}_{j,k-1} \times o^{f}_{j,i,k-1} - p^{f}_{t,i,k-1} \times d^{f}_{i,k-1} \times o^{f}_{i,j,k-1} \right) \quad (2)$$

$$p^{m}_{t+5,i,k} = p^{m}_{t,i,k-1} \times d^{m}_{i,k-1} \ , p^{f}_{t+5,i,k} = p^{f}_{t,i,k-1} \times d^{f}_{i,k-1} \quad (3)$$

$$p^{m}_{t+5,i,100-} = p^{m}_{t,i,95-99} \times d^{m}_{i,95-99} + p^{m}_{t,i,100-} \times d^{m}_{i,100-}$$
$$, p^{f}_{t+5,i,100-} = p^{f}_{t,i,95-99} \times d^{f}_{i,95-99} + p^{f}_{t,i,100-} \times d^{f}_{i,100-} \quad (4)$$

$$N_{t,i,0-14} = \sum_{k=0-4}^{10-14} p^{m}_{t,i,k} \times h^{m}_{i,0-14} + \sum_{k=0-4}^{10-14} p^{f}_{t,i,k} \times h^{f}_{i,0-14} \quad (5)$$

$$N_{t,i,15-64} = \sum_{k=15-19}^{60-64} \left(p^{m}_{t,i,k} \times h^{m}_{i,k} + p^{f}_{t,i,k} \times h^{f}_{i,k} \right) \quad (6)$$

$$N_{t,i,65-} = \sum_{k=65-69}^{100-} p^{m}_{t,i,k} \times h^{m}_{i,65-} + \sum_{k=65-69}^{100-} p^{f}_{t,i,k} \times h^{f}_{i,65-} \quad (7)$$

2.2 Appliance Penetration

Fig.2-1, 2-2 and 2-3 show the relationship between appliance penetrations and the real average income per capita (in 2003 constant yuan) by province for 1990-2003. The statistics on income and penetration were mainly taken from the *China Statistical Yearbook*. Missing data were supplemented by the *Statistical yearbooks of each province*. A relatively high correlation between penetration and income are found. Penetration of air-conditioner seems to have regional characteristics. The figures indicate that the urban appliance penetration is much higher than in rural areas, thus separate curves were fitted to urban and rural data to reflect these differences. Data in Fig.2-1 and 2-3 were fitted logistic curves whereas Fig.2-2 data were fitted logarithmic curves. Based on these six curves, best fitted curves for each province were estimated in a following manner. First, intercepts of these six curves were assumed constant for all provinces. Then, the remaining coefficient was adjusted so that 2003 penetration estimation is closest to actual data recorded in statistical yearbook.

Future income per capita was set as follows. First, we multiplied urban and rural per capita income by respective populations, and estimate total provincial income, for urban and rural areas, in 1995 and 2000. For Base Line Scenario (BL-Scenario), we first assume that rate of total income annual growth in 2000-2020 will be 80 % of the rate in 1995-2000. We then estimated the future per capita income by dividing the total income by population.

2.3 Electricity Consumption

The general framework for estimating REC of each appliance refers to Mahlia et al (2002). Our assumptions related to appliances are as follows. 1) The survival years of refrigerators, color-TVs and air-conditioners were set at 15, 10 and 15 years, respectively. 2) When people buy new appliances for replacement, 80% will buy larger ones and the rest will buy the same size. 3) The size of the appliances are expected to increase from 150, 250, to 350 liters for refrigerator, and 20, 25, to 30 inches for color-TVs. Air-conditioners are expected to change from window-type, split-type(small power), to split-type(large power). 4) These appliances were assumed to move with the expected migration.

In terms of energy efficiency of the three appliances, we mainly refer to the energy efficiency standards provided by *the energy saving low* in China, and supplemented missing information with Japanese equivalent to came up with the following assumptions. We obtain annual electricity consumption [kWh/y] of refrigerators in 2003 in China from ECCJ (2005), and we assume the 1976 energy requirement was of three times that of 2003. Next, we supplement Japanese TV energy efficiency data, and assume 2005 Chinese TV energy efficiency is that of Japanese TV in 1999 (ECCJ: 1998). Also, we assume Chinese TV energy requirement in 1981 is twice that of 2005. Finally, we obtain energy efficiency of air-conditioners in 2005 from ECCJ (2005). We assume the A.C. efficiency in 1976 is two third that of 2005. Specific per household calories needed for air-cooling by province is obtained from Zhang et al (2002). We assume energy efficiency of refrigerators, color-TVs and air-conditioners will improve at 1%, 2% and 2%, respectively. The expected improvements are rather modest since China has already achieved relatively high efficiency level for the three appliances.

As an example, the below shows the equations used to estimate REC of refrigerator at year-T. Equations (8)-(10) and equations (11)-(13) estimate the number of refrigerators in use which

was manufactured in T-14 to T-1 and in T, respectively. REC of refrigerator in year T was calculated by multiplying the number of refrigerator in use by year of production and the specific annual energy requirement by each production year (equation14). Likewise, we calculated REC of the other two appliances.

t : year T : the year; we estimate REC at year T

i, j : urban-rural areas by province

($i, j = 1,2,\cdots,62 \equiv$ urban Beijing, rural Beijing, …, urban Xinjiang, rural Xinjiang)

$RN^{150}_{T,t,i}$: number of 150[l] refrigerator manufactured at year t which exist in i at year T

$IOR_{T,j,i}$: migration rate from j to i at year T

$HN_{T,i}$: household number in i at year T

$RP_{T,i}$: penetration of refrigerator in i at year T

$AREC^{150}_{t}$: annual electricity consumption of 150[l] refrigerator manufactured at year t

$REC_{T,i}$: electricity consumption of refrigerator in i at year T

$$150[l]: RN^{150}_{T,t,i} = RN^{150}_{T-1,t,i} + \sum_{j=1}^{62}\left(RN^{150}_{T-1,t,j} \times IOR_{T,j,i} - RN^{150}_{T-1,t,i} \times IOR_{T,i,j}\right) \quad (8)$$

$$250[l]: RN^{250}_{T,t,i} = RN^{250}_{T-1,t,i} + \sum_{j=1}^{62}\left(RN^{250}_{T-1,t,j} \times IOR_{T,j,i} - RN^{250}_{T-1,t,i} \times IOR_{T,i,j}\right) \quad (9)$$

$$350[l]: RN^{350}_{T,t,i} = RN^{350}_{T-1,t,i} + \sum_{j=1}^{62}\left(RN^{350}_{T-1,t,j} \times IOR_{T,j,i} - RN^{350}_{T-1,t,i} \times IOR_{T,i,j}\right) \quad (10)$$

$$150[l]: RN^{150}_{T,T,i} = RN^{150}_{T-1,T-14,i} \times 0.2 + HN_{T,i} \times RP_{T,i} - \sum_{t=T-14}^{T-1}\left(RN^{150}_{T,t,i} + RN^{250}_{T,t,i} + RN^{350}_{T,t,i}\right) \quad (11)$$

$$250[l]: RN^{250}_{T,T,i} = RN^{150}_{T-1,T-14,i} \times 0.8 + RN^{250}_{T-1,T-14,i} \times 0.2 \quad (12)$$

$$350[l]: RN^{350}_{T,T,i} = RN^{250}_{T-1,T-14,i} \times 0.8 + RN^{350}_{T-1,T-14,i} \quad (13)$$

$$REC_{T,i} = \sum_{t=T-14}^{T} \left(RN^{150}_{T,t,i} \times AREC^{150}_{t} + RN^{250}_{T,t,i} \times AREC^{250}_{t} + RN^{350}_{T,t,i} \times AREC^{350}_{t} \right) \quad (14)$$

2.4 Scenarios

We have two additional Scenarios: Rural Growth Scenario (RG-Scenario) and Energy Efficiency Scenario (EE-Scenario). For the former Scenario, rural income growth rate was set constant at the 1995-2000 growth rate. Urban total income growth is adjusted downward so that provincial level aggregate income figures will equal that of the BL-Scenario. For the latter Scenario, future energy efficiencies are expected to improve faster at 2% annually for refrigerators and 4 % for color-TVs and air-conditioners.

3. Results and Discussions

This section provides the results of the BL-Scenario. Table.1 and 2 show REC for each appliance in 2000 and 2020, respectively.

In urban areas, REC of three appliances is estimated to increase from 122 [TWh/y] in 2000 to 370 [TWh/y] in 2020. The main reason behind the expected urban REC increase is the growth in the number of household, which results from further population concentration and falling household membership [person/household] (Fig 4-1). As shown in Fig.3-1 to 3-3, urban population is expected to increase rapidly, mainly due to internal migration. In addition, expected growth of middle-aged population in urban areas contributes to larger household number, since their HOR is very high. As a result, we expect a large increase in coastal provinces such as Fujian, Zhejiang and Guangdong.

In urban areas, growth in per household REC [kWh/y/household] also contributes, but to lesser extent to the REC increase. This is because penetrations of the three appliances are already

fairly high, and energy efficiencies are expected to improve. For instance, per household REC of refrigerators, color-TVs and air-conditioners are expected to change from 374, 273 and 178 [kWh/y/household] in 2000 to 278, 330 and 607 in 2020, respectively (since most urban household own refrigerators in 2000, future REC of refrigerator decreases with energy efficiency improvement.) Penetration rate of color-TVs and air-conditioners will continue to increase. Also, expected REC increase in warm regions is particularly large because of expected air-conditioner use. For rural areas, REC will also rise considerably (Table 1 and 2), but factors leading to REC increase are quite contrasting from urban counterpart. A change in household number will little affect REC, but increase in per household REC largely contributes to overall rural REC increase. This is because rural population is expected to decease as shown in Fig.3-4 to 3-6, so that household number will be stable despite the declining average household membership. Therefore, rural REC growth is mainly due to the further appliance penetration. In response to expected penetration, per household REC [kWh/y] of refrigerators, color-TVs and air-conditioners are expected to increase from 47, 88 and 5 in 2000 to 220, 152 and 279 in 2020, respectively. Unlike urban equivalent, REC of all appliances is expected to increases largely in rural areas. Yet, per household rural REC of three appliances continue to be lower, about a half of urban area, in 2020. Especially inland provinces such as Guizhou and Qinghai has very low per household REC in 2020, suggesting rural China will continue to have a large potential for REC increase well beyond 2020.

Table.3 shows estimated REC of the three appliances by scenario. REC of the RG-Scenario is 3.7% more than the BL-Scenario in 2020. This is because current appliance penetration in rural areas is much lower than urban, so potential impact from rural REC growth is high. From these scenarios, we can conclude that rural growth plays a key role in determining the future REC in China. Also, REC of the EE-Scenario is 14.1% lower than that of the BL-Scenario in 2020, indicating a large potential for energy-efficiency gain.

Fig.5 compares our estimate of REC of the three appliances and REC from official statistics in 1990-2003, as a way to verify the accuracy of our model. The correlation between the two is very high (R=0.997 for BL-Scenario), suggesting the model reflects well the increasing trend of REC; however, our comparison also suggest that our model may lead to some over-estimation, because our estimate of REC of the three appliances is already about 90% of total REC.

4. Conclusions

REC in China will continue to increase. For the BL-Scenario, REC of the three appliances is expected to increase from 223.8[TWh/y] in 1990 to 510.8[TWh/y] in 2020. The reasons for this increase are as follows.

1) The growth in the number of household in urban areas, resulting from population concentration and falling average household membership. The number of household will increase from 148[million] in 2000 to 305[million] in 2020.

2) The increase in air-conditioner use in warm regions. For example, in urban Guangdong, REC of air-conditioners per household is expected to increase from 731[kWh/y] in 2000 to 1,106[kWh/y] in 2020.

3) The rise in appliance penetration in rural areas. It will cause an increase in REC per household.

The most important of these reasons is 1). Since improving energy efficiency is effective at preventing increases in REC, it will be necessary to strengthen the energy efficiency standards.

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Table.1: annual REC of three appliances in 2000 (estimated by authors)

	Urban REC [MWh/y]				Rural REC [MWh/y]			
	refrigerator	color-TV	air-conditioner	total	refrigerator	color-TV	air-conditioner	total
Beijing	1,883	1,258	710	3,851	362	192	38	592
Tianjin	1,141	740	476	2,358	170	141	22	332
Hebei	2,092	1,429	425	3,946	1,193	1,655	60	2,908
Shanxi	1,135	864	35	2,033	227	668	4	899
Inner Mongolia	975	800	4	1,779	92	331	0	423
Liaoning	2,832	2,047	67	4,946	374	798	2	1,175
Jilin	1,283	1,062	8	2,353	94	440	0	534
Heilongjiang	1,772	1,476	14	3,261	145	567	0	713
Shanghai	2,510	1,754	2,077	6,341	227	125	37	389
Jiangsu	3,904	2,857	1,940	8,701	1,073	1,295	274	2,642
Zhejiang	3,451	2,417	1,961	7,830	1,374	1,207	193	2,773
Anhui	1,859	1,246	563	3,668	392	868	4	1,263
Fujian	1,674	1,245	1,040	3,960	413	725	47	1,185
Jiangxi	1,129	799	305	2,233	125	414	5	544
Shandong	4,483	3,011	1,041	8,535	1,193	1,685	64	2,943
Henan	2,087	1,611	755	4,453	536	1,363	37	1,936
Hubei	3,061	1,902	1,372	6,335	253	543	11	806
Hunan	2,180	1,423	948	4,551	344	704	10	1,057
Guangdong	5,005	4,222	10,097	19,324	583	1,299	205	2,087
Guangxi	1,328	964	655	2,948	96	442	10	548
Hainan	187	213	120	521	14	92	1	107
Chongqing	1,604	1,042	930	3,577	147	352	4	502
Sichuan	2,806	2,080	444	5,330	340	1,092	10	1,443
Guizhou	964	681	20	1,665	64	268	0	331
Yunnan	999	873	2	1,874	120	586	0	706
Tibet	53	46	0	99	2	8	0	9
Shaanxi	1,185	967	257	2,409	131	581	4	716
Gansu	632	560	2	1,194	74	416	1	491
Qinghai	166	129	0	295	6	48	0	54
Ningxia	181	148	1	330	23	116	0	139
Xinjiang	724	483	6	1,213	128	191	0	319
National total	55,285	40,349	26,277	121,911	10,315	19,210	1,045	30,570

Table.2: annual REC of three appliances in 2020 (estimated by authors)

	Urban REC [MWh/y]				Rural REC [MWh/y]			
	refrigerator	color-TV	air-conditioner	total	refrigerator	color-TV	air-conditioner	total
Beijing	2,379	2,831	3,383	8,593	555	381	559	1,495
Tianjin	1,215	1,468	1,871	4,553	235	180	393	808
Hebei	3,057	3,381	3,999	10,438	3,973	2,691	5,074	11,738
Shanxi	1,677	1,673	2,087	5,437	1,737	1,176	756	3,669
Inner Mongolia	1,535	1,858	707	4,100	1,066	699	39	1,804
Liaoning	3,362	3,600	3,575	10,537	1,463	1,050	105	2,618
Jilin	1,681	1,938	1,064	4,683	365	649	31	1,046
Heilongjiang	2,403	2,525	1,469	6,397	775	800	42	1,617
Shanghai	3,296	4,569	6,895	14,760	104	77	201	382
Jiangsu	5,672	6,916	12,682	25,270	2,945	1,851	7,253	12,049
Zhejiang	5,151	6,951	12,011	24,113	1,564	1,232	3,856	6,652
Anhui	2,515	2,673	5,111	10,298	2,666	1,528	1,941	6,135
Fujian	3,135	4,346	9,490	16,971	1,212	926	4,047	6,185
Jiangxi	1,543	1,777	4,592	7,912	1,043	773	270	2,085
Shandong	6,306	6,648	12,402	25,357	4,148	2,651	7,392	14,190
Henan	3,290	3,753	6,118	13,161	5,312	3,205	10,136	18,653
Hubei	3,879	4,174	9,883	17,936	2,053	1,182	3,286	6,521
Hunan	2,650	2,682	7,186	12,519	2,735	1,451	829	5,015
Guangdong	13,453	18,222	54,981	86,656	1,949	1,460	8,557	11,967
Guangxi	2,119	2,250	8,637	13,007	713	875	256	1,844
Hainan	473	466	2,301	3,240	298	199	1,386	1,884
Chongqing	1,836	2,350	3,093	7,279	1,278	727	389	2,394
Sichuan	3,718	4,304	6,697	14,719	3,639	2,191	3,215	9,045
Guizhou	1,457	1,456	679	3,592	235	595	18	848
Yunnan	2,205	2,641	186	5,032	1,040	1,268	10	2,318
Tibet	105	119	24	248	12	23	1	35
Shaanxi	1,968	2,262	3,003	7,233	1,481	1,065	149	2,695
Gansu	968	1,123	316	2,407	1,293	930	13	2,236
Qinghai	235	258	0	493	124	115	0	239
Ningxia	297	316	111	725	331	269	8	608
Xinjiang	1,089	1,050	332	2,471	1,255	609	40	1,903
National total	84,668	100,584	184,886	370,137	47,599	32,828	60,253	140,680

Table.3: REC of three appliances by Scenario (estimated by authors)

	Scenarios	1990	1995	2000	2005	2010	2015	2020
REC of three appliances [TWh/y]	BL	43.5	81.8	152.5	246.4	348.3	443.7	510.8
	RG	43.5	81.8	152.5	245.9	357.3	465.7	529.9
	EE	43.5	81.8	152.5	246.2	340.3	414.4	447.6

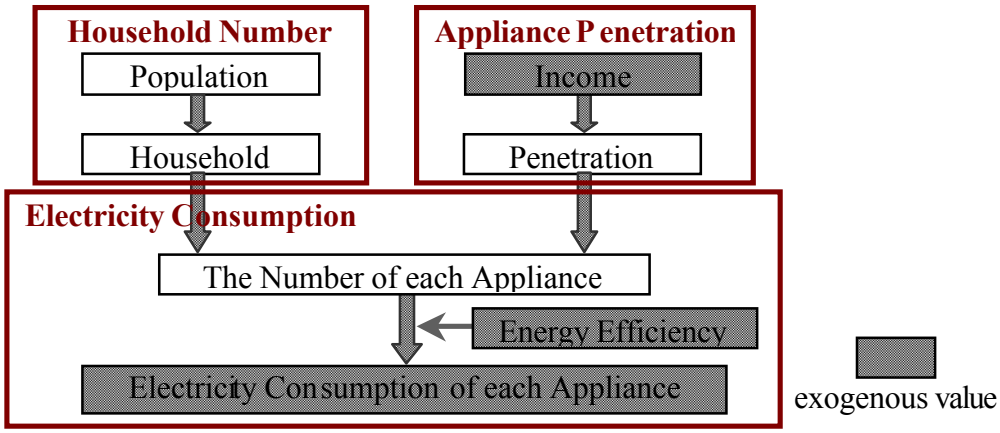


Fig.1: Scheme of the model

Fig.2-1: penetration of refrigerators and average income for 1990-2003

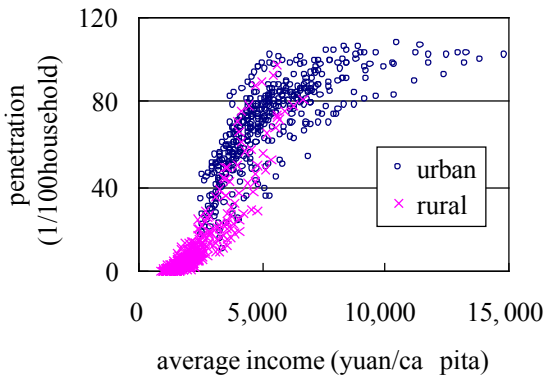


Fig.2-2: penetration of color-TVs and average income for 1990-2003

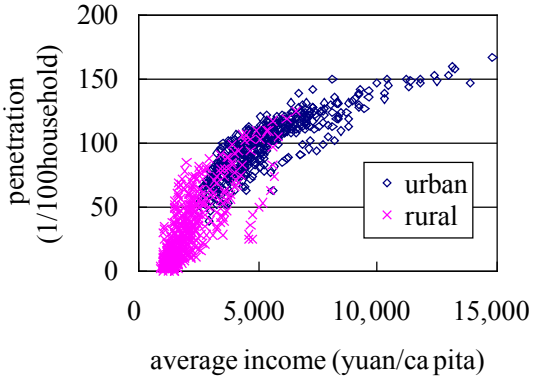


Fig.2-3: penetration of air-conditioners and average income for 1990-2003

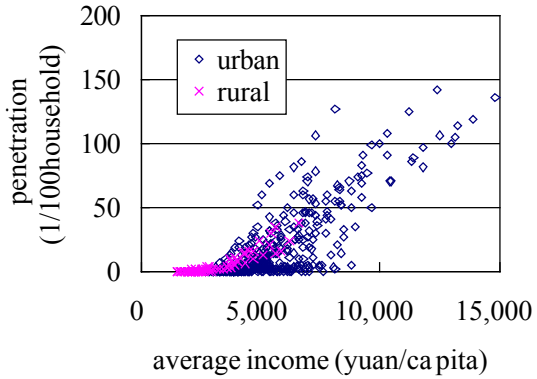


Fig.5: REC for 1990-2003

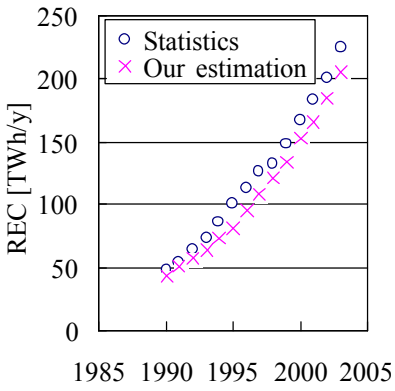


Fig.3-1: Urban population in 1980

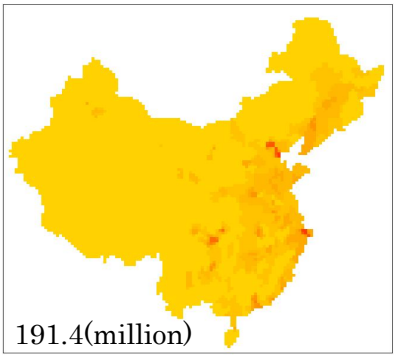


Fig.3-2: Urban population in 2000

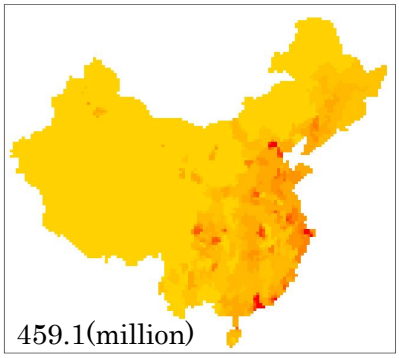


Fig.3-3: Urban population in 2020

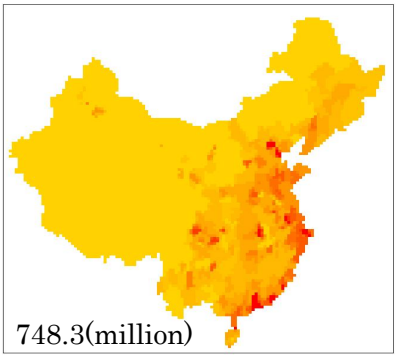


Fig.3-4: Rural population in 1980

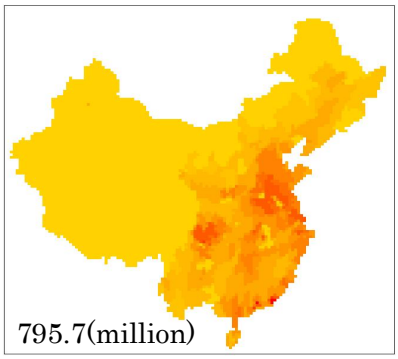


Fig.3-5: Rural population in 2000

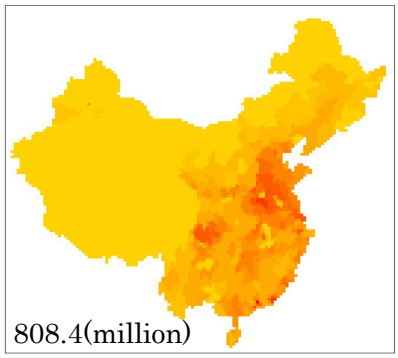
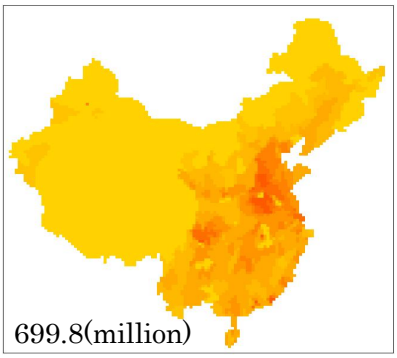


Fig.3-6: Rural population in 2020



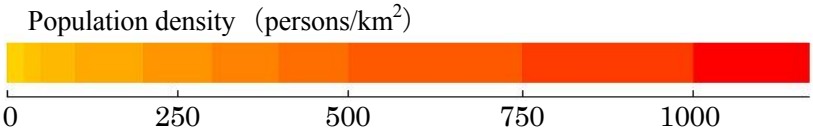


Fig.4-1: Household number and membership in urban China

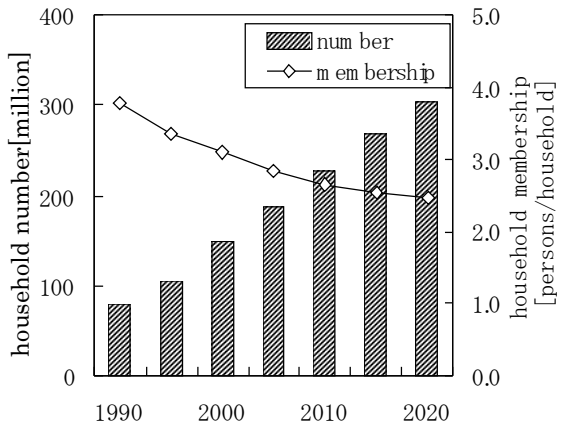


Fig.4-2: Household number and membership in rural China