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BIOMASS, BIOGAS AND MUNICIPAL WASTE AS ALTERNATIVE ENERGY SOURCES FOR HISTORICAL CITIES

Various energy sources available for using in historical cities were analyzed taking account of their impact an environment and sustainable development of a city. The article is focused on biomass – only about 1.5% of the world biomass resource base is currently utilized. An analysis of the investment, fuel and o&m costs was presented for five power-generating plants and two thermal-electric power stations fuelled by biomass, municipal waste and biogas. Electricity costs varied from "free" (due to a large credit for burning municipal waste) to 100.50 USD/MWh for the power-generating plants, and from 63.00 to 144.50 USD/MWh for the thermal-electric power stations.

1. CURRENT PRIMARY ENERGY USE

Historical cities rely on a wide range of energy sources to meet the daily needs of individual users and companies. The main uses of energy in these cities usually include heating, air conditioning (in warm climates), transportation and various electrical applications. In the 20th century, energy use increased at an unprecedented rate – fossil fuel consumption increased more than 20-fold and the use of traditional energy sources tripled [15]. Table 1 contains basic information on the current aggregate world energy supply. Renewable energy sources represent only 12.2% (54.6 EJ) of the total world primary energy consumption. In a sense, the share of "clean" renewable energy sources is actually lower since biomass is often used in a non-renewable way where consumption exceeds production.

Clearly, the current dependence on fossil fuels is great. Moreover, it is not sustainable. A widely used indicator for the amount of energy reserves is the R/P (reserves/production) ratio expressed in years. Table 2 shows the R/P ratios for the three

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Table 1

Current world primary energy supply

	World energy supply (2002)					Electricity			Heat		
	Primary energy			Total	renew.		Total	renew.		Total	renew.
	[Gt]	[Tcm]	[EJ]	[%]	[%]	[TWh]	[%]	[%]	[EJ]	[%]	[%]
Oil	3.65		152.7	34.1		1 161	7.3		0.94	7.9	
Natural gas		2.62	98.8	22.0		3 065	19.2		6.00	50.4	
Coal	4.79		115.6	25.8		6 120	38.3		4.09	34.4	
Hard coal	3.91		108.0	24.1		5 363	33.6		3.37	28.3	
Brown coal	0.88		7.6	1.7		757	4.7		0.72	6.1	
Nuclear			26.4	5.9		2 660	16.7				
Biomass*			44.00	9.82	80.5	172	1.08	5.8	0.51	4.3	59.6
Hydro*			9.63	2.15	17.6	2 676	16.77	90.6			
Geothermal*			0.60	0.13	1.1	52	0.33	1.8	0.15	1.2	17.1
Wind*			0.19	0.04	0.3	52	0.33	1.8			
Solar			0.21	0.05	0.4	2	0.01	0.1	0.20	1.7	23.3
TOTAL			**448.1**	**100.0**		**15 960**	**100.0**		**11.90**	**100.0**	
RENEWABLE (*)			**54.6**	**12.2**	**100.0**	**2 954**	**18.5**	**100.0**	**0.86**	**7.2**	**100.0**

Source: own calculations based on [2], [7], [8], [9], [10], [12], [15], [16].

primary fossil fuels*. It demonstrates how long resources that are profitable to explore, i.e. reserves, would last at current production rates.

Table 2

World reserves/production (R/P) ratios for fossil fuels

Fossil fuel type	Reserves/ Production
Oil	about 40 years
Natural gas	about 60–67 years
Coal	about 185–200 years

Source: based on [1], [3], [7], [18].

It is very important, especially in the context of historical cities, to consider, unintended consequences associated with the burning of fossil fuels to produce heat and electricity. Primary environmental concerns are the effects described below on humans, plants and animals. They are as follows:

- global warming, primarily associated with CO_2 emissions,

* A detailed discussion of reserves, reserves growth, resources, and undiscovered resources is beyond the scope of this article. Briefly, as proven reserves are depleted, through exploration and technological advances some new reserves are discovered and/or the exploitation of previously found resources becomes profitable. The point here is not that all resources will be depleted, but that fossil fuels are becoming increasing scarce as exploitation goes on at a high rate.

• other pollutants released into the atmosphere during the burning of fossil fuels, such as NO_X, SO_X, mercury, lead, and fine particulate matter.

Some groups are lobbying for increasing the share of nuclear energy. This option has three main disadvantages compared to renewable energy sources:

• nuclear fuel (mostly uranium) supply is limited,

• long-term storage of waste is a problematic and highly contentious social issue,

• concern about nuclear fuel or waste being used by terrorists, and the threat of nuclear power plants or processing facilities becoming the target of terrorist attacks.

2. IDENTIFICATION AND QUANTIFICATION OF ALTERNATIVE/CLEAN/RENEWABLE ENERGY SOURCES

Let us now consider the potential for the development of alternative, renewable energy sources: biomass, hydro, wind, solar and geothermal. Table 3 shows the po-

Table 3

World potential of renewable energy sources

Renewable energy type	Approximate total resource base [EJ/year]	Multiple of current total world energy use[1]	Current use [EJ] [(% of total)]
Biomass	2 900	7 ×	44[2] (1.5%)
Hydro (conventional)	60	0.14 ×	9.6 (16%)
Hydro (oceans[4])	7 400	17 ×	Negligible [3]
Wind	1 800	4 ×	0.2 (0.01%)
Solar (available) for conversion[5]	1 600–50 000	4–117 ×	0.2 (<0.01%)
Geothermal (useful accessible resource base[6])	600 000	1 402 ×	0.34 (0.00006%)
TOTAL	>613 760	>1 427 ×	54.34 (<0.01%)

[1] Rounded off to nearest integer, except multiples smaller than one; current total world energy use (total primary energy supply (TPES)) is about 430 EJ.

[2] Of this, only 6 EJ in modern uses, the remaining 38 EJ in inefficient traditional uses.

[3] There do exist some experimental power stations using this energy, such at La Rance in France.

[4] Includes tidal, wave, thermal and salt gradient energy.

[5] Total solar radiation reaching the earth is about 2 900 000 EJ, about 1 600–50 000 is available based on different assumptions on annual clear sky irradiance, annual average sky clearance, and available land area [15], [18].

[6] The amount of heat that could theoretically be tapped within a depth of 5 km is far greater: about 140 million EJ.

Source: own calculations based on [6, 9, 11, 15, 17, 18].

tential of major renewable energy sources* expressed in terms of energy content (EJ/year) and as a multiple of total current energy use. The rightmost column shows to what extent the resources are currently being utilized. The single largest resource, accounting for more than 90% of total renewable energy sources, is geothermal energy. The useful (accessible) amount of this type of energy is 600 000 EJ – roughly 1 400 times the current world energy consumption of 430 EJ. Biomass has a resource base of about 2 900 EJ – roughly 7 times current world energy use. The land requirements for harvesting biomass, usually in the form of energy crops such as willow or poplar, are a significant obstacle to further development. Nevertheless, there is much potential for increased use of biomass and biofuels – only about 1.5% of the resource base is currently being utilized.

The quantity and financial implications of utilizing all renewable energy sources must be carefully considered when choosing the energy mix for a particular historical city.

3. POTENTIAL FOR BIOMASS** AND MUNICIPAL WASTE USE IN HISTORICAL CITIES

For historical cities (as in other locations), the decision to adopt a particular source of energy will likely be based on three primary considerations:

- technical – ability to produce the energy to meet the needs of the city,
- environmental – to minimize pollution of the air, water and soil,
- financial – the cost of the alternative energy source must be reasonable.

From the environmental perspective, whenever possible, the following energy sources are preferable since they have minimal environmental impact: geothermal, wind and solar. However, not all cities have access to geothermal energy, whereas wind and solar power output is intermittent and not economical at many locations. Hydro-generation is also limited to locations with adequate resources. Tables 3 and 4 show the significant potential for increased use of biomass. Especially if it is used in a sustainable way (i.e. consumption ≤ production), biomass is less polluting than fossil fuels***. Biomass is a resource that is available in many areas and can be used to produce a variety of useful energy sources:

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* The table does not include hydrogen, viewed by some as the fuel of choice for the 21st century. Hydrogen is not included since using existing technology, more energy is required to produce the hydrogen from water than can subsequently be obtained from burning it. Thus, for the purpose of this discussion, hydrogen is viewed as an important energy carrier, not an energy source.

** Including solid biomass, biogas and liquid biofuels.

*** During combustion, biomass releases the carbon dioxide previously captured from the atmosphere by plants. Therefore, biomass combustion does not increase global CO_2 concentrations.

- solid biomass and biogas, for heating and electricity generation,
- liquid biofuels, mainly for the transportation sector and heating.

Table 4

World biomass, waste, biogas and biofuel production and resources

Total resource use		Production/year in 2002		Resources	Theoretical potential
	[EJ/year]	Heat [EJ/year]	Electricity [TWh/year]	[EJ/year]	[EJ/year]
Biomass and waste		0.51[1]	172.0		
Biomass	44			>276	2 900
traditional[2]	38	38			
modern[3]	6	0.226	116.1		
Industrial waste		0.093	19.1		
Municipal waste		0.186	36.8		
Biogas		0.008	23.0		
Liquid biofuels	0.33				

[1] In accordance with source data, heat and electricity production totals for biomass do not include traditional uses.
[2] Mainly wood.
[3] Steam, electricity and biofuel production.
Source: own calculations based on [4], [5], [14], [15], [16].

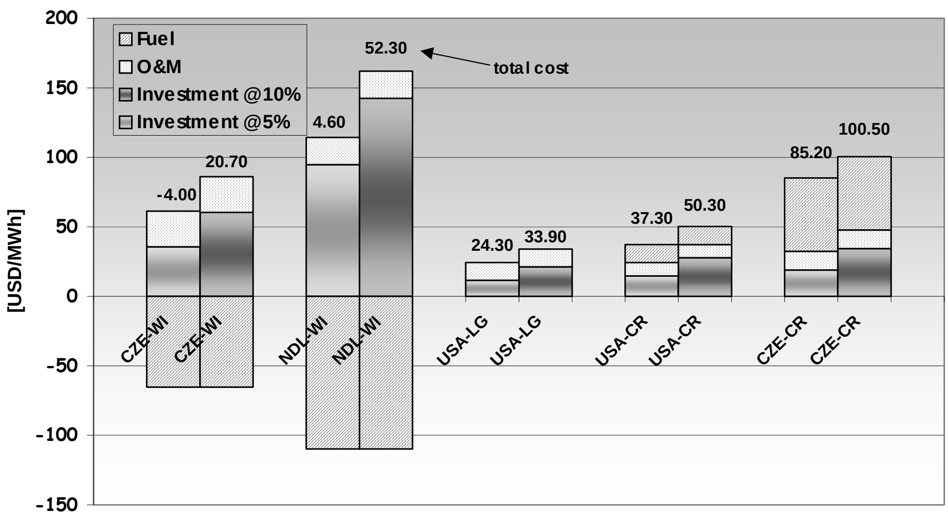

Fig. 1. Cost of electricity from biomass-fuelled generation plants
Source: own graph and calculations based on data from [13]

It is beyond the scope of this article to provide a detailed comparison of all energy sources for historical cities. Instead, we will provide some details pertaining to biomass as an alternative energy source that may be suitable for some historical cities. Since the decision to adopt a particular fuel source would probably be economic, this aspect will be our main focus.

First we will deal with electricity generated at five plants: two fuelled by biomass (marked as CZE-CR and USA-CR), two by municipal waste (CZE-WI and NDL-WI) and one by landfill gas (USA-LG). Their construction costs were 1700 and 2178 USD/kWe for the biomass ones, 3630 to 7013 USD/kWe for the ones fuelled by waste and 1476 USD/kWe for the one running on biogas (landfill gas). Figure 1 shows the cost of energy from the above plants, arranged from the lowest to the highest cost (at an interest rate of 5%).

Table 5 provides an analysis the basic data, such as lifetime, capacity, efficiency, construction cost and cost of energy for these plants. The energy cost is based on fuel, operations and maintenance (o&m) and investment costs.

Table 5

Biomass-, biogas- and waste-fuelled generation plants: efficiency, construction cost and electricity cost

	min	max	μ	$\%\mu$	σ
Number of generation plant			5		
Lifetime [years]	15	40	35.0		11.2
Capacity [Mwe]	10.0	100.0	41.7		38.2
Electrical efficiency	25.0%	38.3%	31.5%		6.4%
Construction cost [USD/kWe]	1 476	7 013	3 199		2 291
Cost of electric energy [USD/MWh] at a 5% discount rate					
Investment	11.50	94.70	35.10	119.1%	34.59
o&m	9.60	25.70	16.24	55.1%	6.43
Fuel	–109.80	52.80	–21.86	–74.1%	64.98
Total	–4.00	85.20	29.48	100%	35.12
Cost of electric energy [USD/MWh] at a 10% discount rate					
Investment	21.10	142.40	57.16	110.9%	49.92
o&m	9.60	25.70	16.24	31.5%	6.43
Fuel	–109.80	52.80	–21.86	–42.4%	64.98
Total	20.70	100.50	51.54	100%	30.26

Notes: min and max costs, total energy costs calculated for given generating plants (not as the sum of min and max fuel, o&m and investment costs for the separate plants); efficiency based on the lower heating value (LHV), μ = average, σ = standard deviation.

Source: own calculations based on data from [13].

At a discount rate of 5%, average investment costs are 35.10 USD/MWh, at a 10% discount rate they increase to 51.54 USD/MWh. Large differences in the cost of electric energy are mainly due to considerable variation in the fuel costs. The fuel cost was negative for the plants burning municipal waste – it was a credit amounting to 109.80 and 65.30 USD/MWh. In fact, the credit for the second one outweighed the investment and o&m cost, providing, in effect, 'free' electricity. Landfill gas was free. For the plants fuelled by biomass, fuel cost varied from 13.00 to 52.80 USD/MWh. The total costs for each plant are shown in figure 1.

We also analyzed data from two thermal-electric power stations: one fuelled by biogas (DEU-CHP5), with a construction cost of 2562 USD/kWe, and the other burning biomass (AUT-CHP2), with a construction cost of 3718 USD/kWe. Figure 2 shows the cost of energy for both plants.

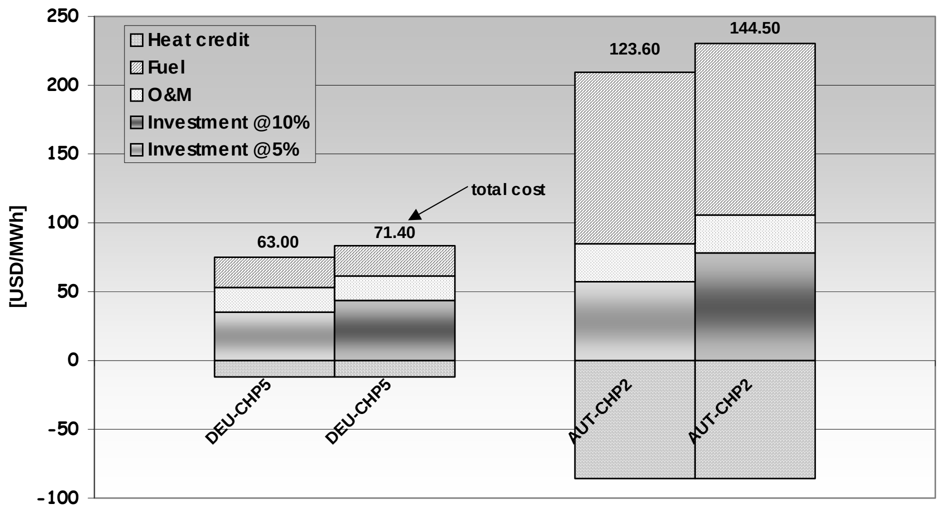

Fig. 2. Cost of electricity from biomass-fuelled thermal-electric power stations
Sources: own graph and calculations based on data from [13]

A credit for heat had a strong influence on electricity costs: it amounted to 12.00 and 85.80 USD/MWh in terms of reducing electrical energy costs. Table 6 lists key data for both plants.

The cost of electricity from the plant fuelled by biogas approached 63.00 USD/MWh (at a discount rate of 5%) or 71.40 USD/MWh (at a discount rate of 10%). For the plant burning biomass these were 123.60 USD/MWh and 144.50 USD/MWh, respectively. In this example, due to considerably higher investments, despite the higher efficiency, electricity from thermal-electric power stations was actually more expensive than from conventional plants. Obviously, these costs would vary for different cities, reflecting mainly diverse fuel sources and prices.

Table 6

Biogas- and biomass-fuelled thermal-electric power stations:
efficiency, construction cost, heat credit and electricity cost

	Biogas	Biomass	μ	%μ	σ
Number of plants:			2		
Lifetime [years]	20	15	17.5		3.5
Capacity					
electrical [MWe]	1.0	8.0	4.5		4.9
heat [MWth]	1.5	20.0	10.8		2.0
Efficiency					
electrical	35.0	n/a			
combined	n/a	80.0%			
Construction cost [USD/kWe]	2 562	3 718	3 140		817
Cost of electric energy [USD/MWh] at a 5% discount rate					
investment	35.20	57.30	46.25	32.5%	15.63
o&m.	17.80	27.50	22.65	15.9%	6.86
fuel	22.00	124.60	73.30	51.5%	72.55
(heat credit)	–12.00	–85.80	–48.90	–34.4%	52.18
total	63.00	123.60	93.30	100%	42.85
Cost of electric energy [USD/MWh] at a 10% discount rate					
investment	43.60	78.20	60.90	38.8%	24.47
o&m.	17.80	27.50	22.65	14.4%	6.86
fuel	22.00	124.60	73.30	46.7%	72.55
(heat credit)	–12.00	–85.80	–48.90	–31.2%	52.18
Total	71.40	144.50	107.95	100%	51.69

Notes: min and max costs, total energy costs calculated for given generating plants (not as a sum of min and max fuel, o&m, investment costs and heat credit for separate plants); n/a = not available efficiency based on lower heating value (LHV), μ = average, σ = standard deviation.

Source: own calculations based on data from [13].

BIBLIOGRAPHY

[1] British Petroleum (BP), *Statistical Review of World Energy 2004*, 2004, London, BP.

[2] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), *Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen 2002*, 2002, Hannover, BGR.

[3] Cedigaz, *Natural Gas in the World*, Rueil-Malmaison (France), Institut Français du Pétrole, 2004.

[4] D'APOTE S.L., *IEA Biomass Energy Analysis and Projections. Biomass Energy: Data, Analysis and Trends*, Proceedings of the OECD and IEA Conference, 23–24 March, 1998, Paris.

[5] FISCHER G., HEILIG G.K., *Population Momentum and the Demand on Land and Water Resources*, Report IIASA-RR-98-1, Laxenburg (Austria), 1998, International Institute for Applied Systems Analysis.

[6] GORLOV A.M., *Tidal Energy*, Boston, 2001, Northeastern University Academic Press.

[7] International Energy Agency (IEA), *Coal Information 2004*, Paris, 2004a, IEA.

[8] International Energy Agency (IEA), *Electricity Information 2004*, Paris, 2004b, IEA.

[9] International Energy Agency (IEA), *Key World Energy Statistics*, Paris, 2004c, IEA.
[10] International Energy Agency (IEA), *Natural Gas Information 2004*, Paris, 2004d, IEA.
[11] International Energy Agency (IEA), *Renewables Information 2004*, Paris, 2004e, IEA.
[12] International Energy Agency (IEA), *World Energy Outlook 2004*, Paris, 2004f, IEA.
[13] International Energy Agency (IEA), Organization for Economic Co-operation and Development (OECD) and Nuclear Energy Agency (NEA), *Projected Costs of Generating Electricity*, Paris, 2005, OECD/IEA.
[14] NAKICENOVIC N., GRÜBLER A., MCDONALD A., *Global Energy Perspectives*, Cambridge, 1998, Cambridge University Press.
[15] United Nations Development Programme (UNDP), United Nations Department of Economic and Social Affairs (UN-DESA) and World Energy Council (WEC), *World Energy Assessment (WEA): Energy and the Challenge of Sustainability*, New York, 2000, UNDP.
[16] United Nations Development Programme (UNDP), United Nations Department of Economic and Social Affairs (UN-DESA) and World Energy Council (WEC), *World Energy Assessment (WEA): Overview 2004 Update*, New York, 2004, UNDP.
[17] World Energy Council (WEC), *New Renewable Energy Resources: A Guide to the Future*, London, 1994, Kogan Page Limited.
[18] World Energy Council (WEC), *Survey of Energy Resources 2004*, London, 2004, WEC.

BIOMASA, BIOGAZ I ODPADY KOMUNALNE JAKO ALTERNATYWNE ŹRÓDŁA ENERGII DLA MIAST HISTORYCZNYCH

Omówiono źródła energii dla miast historycznych, biorąc pod uwagę ich wpływ na środowisko naturalne oraz aspekt zrównoważonego rozwoju. Rozważania koncentrują się na biomasie, której zasoby są obecnie wykorzystane jedynie w około 1.5%. Przedstawiono analizę kosztów inwestycji, paliwa oraz eksploatacji dla pięciu elektrowni oraz dwóch elektrociepłowni, w których spala się biomasę, odpady komunalne i biogaz. Koszty energii elektrycznej w badanych elektrowniach wynoszą od zera (dochód za spalanie odpadów komunalnych pokrył pozostałe koszty) do 100,50 USD/MWh, oraz od 63 do 144,50 USD/MWh a elektrociepłowniach.