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A COMPARATIVE STUDY OF THE TOTAL ENVIRONMENTAL COSTS ASSOCIATED WITH ELECTRICAL GENERATION SYSTEMS*

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Abstract—Modern technological societies require adequate reliable electrical power, and as technology and information transfer and electronic processing increases, the reliance on centralized and/or decentralized electrical supply systems will increase. A study identifying and comparing the Total Environmental Costs (TECs) associated with Electrical Generation Systems (EGS) has been undertaken and the major findings presented in the following paper.

This study discusses environmental impacts of EGS on air, water and land and evaluates the magnitude of the impacts in terms of resource use and/or loss and their associated dollar costs where available. Electrical generation systems considered are limited to those systems with a proven technological record.

It is concluded that EGS using wind energy renewable resources had the lowest TEC followed by small hydro, solar thermal, solar photovoltaic and geothermal. Biomass and waste-to-energy ranked with nuclear above fossil fuels when operated renewably. Natural gas was followed by oil then coal which ranked last.

1. INTRODUCTION

The major findings of a study to identify and compare the Total Environmental Costs (TECs) associated with Electrical Generation Systems (EGS) are presented which were developed from a variety of reference materials, reports and mandated rules and regulations. The study is an on-going research effort which is intended to assist future planning and development of EGS systems. The paper is an overview of the subject which is changing nearly daily in response to factors such as the 'greenhouse' effect and adverse impacts of present EGS systems. The role of examining TECs for EGSs is essential if a holistic approach is to be considered in meeting future needs of operating and developing central and decentralized systems which meet the desired and mandated societal environmental goals.*

1.1. *The concept of Total Environmental Costs (TECs) and externalities*

The purpose in using a term such as TECs is an attempt to develop total system estimates of the on-site and off-site environmental, resource and financial impacts associated with fuel procurement, EGS development and operation, electrical transmission, waste disposal and decommissioning and to compare and contrast these impacts to the EGS capital costs. While it is necessary and important to consider and present 'externality' costs meaning 'unpaid values, benefits or damages', other measures of impacts to the environment and resources are useful as an aid to comparing TECs.

1.2. *Parameters to be considered in assessing TECs*

Systems discussed include central and decentralized renewable resources including solar photovoltaic (PV) and thermal, wind, hydroelectric (hydro), geothermal, biomass, waste-to-energy (WTE); fossil fuel including coal, oil and natural gas; and nuclear.

Parameters discussed include: capital and externality costs; land disturbance; air emissions of nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM), carbon dioxide as carbon (C); water use and liquid waste disposal; wastes from air emission control systems (AECS) such as fly ash, scrubber materials and hazardous wastes; fuel residuals such as bottom ash; and the production and disposal of noxious and hazardous wastes such as asbestos, heavy metals, radioactivity and air toxics.

1.3. *EGS environmental on-site and off-site impacts*

Each central station EGS includes the TECs of the impacts of the immediate power plant installation and operation and the necessary power transmission line interties. Added to the on-site impacts, which may be low, are often high off-site impacts such as fossil and nuclear fuel production which may include strip and

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tunnel mining, oil and gas production wells, gathering and transportation facilities, fuel processing, and storage and transportation, which should be included when assessing their respective TEC impacts. EGS systems are highly diverse and vary greatly depending upon their location and where and from what their energy source is derived.

EGS systems which may have low on-site TECs and the lowest capital costs, such as natural gas fired power plants, are often serviced by long gas pipeline(s) which may stretch thousands of miles from the production field where the fuel is produced. Along the natural gas transport system, losses and impacts occur during fuel processing to remove pollutants which are often flared, periodic pumping, storage, and possible cryogenic trans-oceanic shipping with evaporative losses. While natural gas EGS capital costs are low, when the capital costs are added to the externalities costs, the total is approaching the capital costs of present decentralized solar photovoltaic EGS which avoids the 6% to 12% electrical transmission losses and their TECs.

2. EGS FUEL, CAPITAL AND EXTERNALITY COSTS AND LAND DISTURBANCE COMPARISON

The land disturbance of each EGS and supporting system varies greatly. The simple low energy dispersed EGS solar PV panels which provide power on-site for often remote systems are highly useful with little land disturbance but, when used for central power EGS, land disturbance is a major consideration. Complex high energy EGS TECs are often difficult to quantify such as international coal mining with shipping of processed coal trans-oceanic to EGS systems located deep within continents.

A summary of estimated EGS fuel input energy content, capital costs, land disturbance and externality costs per megawatt electric (MWe) is listed in Table 1. Air pollutant emissions which have regional, national and global impact potential, hazardous wastes and water impacts are discussed separately in the following sections. The listings in Table 1 demonstrate that wind energy has the lowest land disturbance, capital and externality costs while coal has the highest. Major considerations of each EGS are briefly discussed.

2.1. *Solar photovoltaic (PV) and solar thermal*

Solar systems without storage systems or cogeneration are limited to daylight operations. While practical solar thermal systems are sited in desert regions, solar photovoltaic systems are useful in a wide range of high and low energy settings. Solar energy has a global average energy availability at the surface of 190 W/m^2 (1 Btu/ft2-min). Solar PV panels and solar thermal parabolic reflecting heating boiler systems have the ability to convert 10%–15% of this available energy into electricity. Capacity factors are estimated to average 34% for solar PV, and 24% for solar thermal. Conversion efficiencies and costs are estimated to decrease markedly in the future as forecast in the United States of America (U.S.) National Energy Strategy [13].

2.2. *Wind*

Centralized wind farming EGS in California, due to the daily thermal-induced marine intrusion, has steadily increased with 1,500 MWe presently installed. Wind potential for California is estimated at 6,500 MWe with an average capacity factor of 30%. Generation is limited to windy days and high energy to areas where an EGS can generate 0.2–0.3 kW/m^2 at a good site to $>$0.3 kW/m^2 at an excellent site. Typically excellent sites are ridge tops where steady winds average 8 mps (20 mph) [1].

2.3. *Geothermal*

Known geothermal resource areas (KGRAs) in the U.S. have been estimated by the U.S. Geological Survey at 23,000 MWe. Geothermal energy has low environmental impacts and most KGRAs are located in remote volcanic and desert areas where population densities are low. Urban air districts with air pollution problems have requested significantly increased use of geothermal EGS as a means of improving air quality [2]. The ability of geothermal energy to supply reliable EGS has been demonstrated at The Geysers KGRA in Northern California where the world's largest development has supplied EGS systems for over 50 years, with presently 1,500 MWe on line.

2.4. *Hydroelectric (Hydro)*

Hydroelectric (hydro) EGS are difficult to categorize since often the installations have several functions including flood control, water conservation and storage, irrigation and diversion, and include centralized large scale and decentralized small scale. Climatological and topographic settings and functions cause large variations in EGS capital costs, power potential, land disturbance and externality costs. Most available large hydro sites in the U.S. have been developed and new large hydro developments face intense environmental opposition while small and retrofit hydro development has little opposition.

Table 1. Electrical Generation Systems' environmental land disturbance

Electrical Generation System (EGS)	Fuel energy content or power capacity factor	Fuel proximity capital cost ($/MWe)	Land disturbance [hectare/MWe (acre/MWe)] Externality [10] ($-plant life/MWe)
Solar—photovoltaic:			
	190 W/m^2	On-site $5.6MM [7]	2–4 (5–10)
	(1 Btu/ft^2 min)	centralized	$0.17MM
	32% U.S.A. [7]	decentralized	$0.12MM
Solar—thermal:			
	190 W/m^2 (1 Btu/ft^2 min)	On-site $3.4 MM [7]	4(10)
	24% U.S.A. [7]		$0.13MM
Wind—selected wind farm energy sites:			
	0.2–0.3 kW/m2 good	On-site	0.14–0.40
	>0.3 kW/m^2 excellent	$1.1MM [7]	(0.35–1.0)
	22% U.S.A. [7]		$0.081MM
Geothermal:			
	0.36 kW-hr/kg	On-site	2.0
	550 Btu/lb at 100 psi	$2.2MM [7]	(5.0)
	81% U.S.A. [7]		$0.43MM
Hydroelectric:			
	Impoundment 112 MWe	On-site	3.8 (9.4) $0.15MM
	pump storage 1000 MWe [7]	on-site	0.8 (2.0)
	river run 200 MWe [7]	on-site	0.8 (2.0)
	small hydro <30MWe [8]	on-site	0.8 (2.0)
	55% [8]	$2.0MM [8]	$0.20MM–$0.35MM
Biomass:			
	4.2–6.1 kW-hr/kg	Off-site	0.8
	6500–9500 Btu/lb	$1.6MM	(2.0)
	70% U.S.A. [7]		$1.3MM–$1.8MM
Waste-to-energy			
	0.66 kW-hr/kg	Off-site	0.8
	600 kW-hr/ton [11]	$3.8MM[12]	(2.0)
	80% [12]		$8.0MM–$11MM [12]
Fossil fuel—conventional coal:			
	7.4 kW-hr/kg	Off-site	2.0–8.4
	12,000 Btu/lb	$1.8MM	(5.0–21)
	80% [4]	existing 1.2% sulfur	$14MM–$18MM
		U.S. NSPS	$9.5MM–$12MM
Fossil fuel—natural gas and oil:			
	14 kW-hr/kg-oil	Off-site	2.0
	16 kW-hr/kg-oil	$1.5MM	(5.0)
	21,000 Btu/lb-oil	oil boiler 1% sulfur	$9.6MM–$12MM
	25,000 Btu/lb-gas	oil turbine 1% sulfur	$6.4MM–$7.9MM
	81% [4]	natural gas existing	$2.6MM–$3.2MM
		natural gas BACT	$1.7MM–$2.1MM
Nuclear—conventional boiling water reactor:			
	3.6 MM kW-hr/kg	Off-site	1.0 (2.5)
	5,500MM Btu/lb	$1.5MM [8] to $4.7MM [13]	$5.4MM–$7.6MM
	70% [4]	decommissioning $1.0MM [10]	

2.5. *Biomass*

Biomass EGS can be renewable if tree planting and re-growth are balanced with biomass energy consumption [23]. Many biomass EGS utilize forestry and agricultural wastes which would otherwise be open field burned or left to decay. Toxic air emissions and hazardous ash wastes emission controls are increasing the capital and operational costs of biomass EGS.

2.6. *Waste-to-Energy* (*WTE*)

The production and composition of municipal wastes vary widely from rural communities to industrial urban cities. In many areas the crisis in siting new garbage landfills has necessitated utilization of increased recycling, biomass composting, and the development of WTE facilities. Municipal wastes comprise on the average 70% paper, yard trimmings, textiles and food, with fossil fuel produced waste making up about 10% and the remainder metals, glass and inert materials [3]. Toxic air emissions and hazardous ash wastes emission control are increasing the capital and operational costs of WTE EGS.

2.7. *Coal*

A typical 500 MWe coal EGS with an 80% capacity factor is usually fueled by a 146 h/yr (365 acre/yr) strip mine. This requires transport of 90 clean processed coal train loads per year, with a 1,400 mile round trip, powered by four 3,000 hp diesel locomotives with 105 cars each containing 100 tons of coal [4]. A typical recently proposed 2,000 MWe coal plant neglected off-site TECs of coal mining, processing and transportation. Impacts from related emissions were not considered even though the project would have required 4–5 coal train deliveries of 55 cars each of 100 tons per day of operation [5].

2.8 *Oil and natural gas*

Oil, natural gas and propane gas EGS are typically serviced by pipelines or by tanker delivery. Natural gas tanker delivery requires cryogenic cold liquid shipping. Natural gas is processed to remove pollutants such as sulfur bearing compounds which enables EGS to have virtually no SOx emissions. Oil is typically processed to lower sulfur content but the process is more expensive. Clean oil and gas EGS are serviced by an oil and gas field, fuel processing and transportation which have their respective cumulative pollution impact TECs.

Clean burning fuels such as natural gas have lower air emissions than other fuels but must also be accountable for their off-site production, processing and transportation impacts. While the TECs of EGS are particular to each application setting, it is possible to gain an insight into off-site losses through available statistics. World-wide flaring of natural gas during 1986 was estimated to account for 6% of natural gas use and 1% of the carbon dioxide emissions from all fossil fuel use.

Resource conversion losses during processing and distribution of fuel used for internal combustion engines have been estimated in gasoline production at 17%, in natural gas methanol at 11% and for CNG (cryogenic natural gas) at 24%. The estimated off-site and final EGS or vehicle use carbon emissions of methanol produced from natural gas are shown in Fig. 1 for extraction, gas handling, methanol conversion, tanker or pipeline transport and trucking distribution, and total 23% [6].

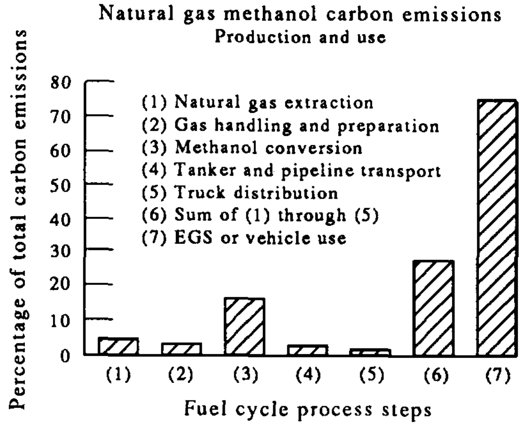

Fig. 1. Methanol production and use carbon emissions.

2.9. *Nuclear*

The absence of a U.S. radioactive waste disposal program; the TECs of mining, fuel processing, radioactive materials handling, decommissioning and clean-up; and the cost of the necessary fail-safe air and water emission control systems has resulted in no scheduled new nuclear EGS in the U.S. Past planning has drastically under-estimated capital costs at \$1.6MM/MWe and the most recently completed plant cost \$4.7MM/MWe [8, 20].

3. ADVERSE EFFECTS OF AIR-BORNE POLLUTANT EMISSIONS

A timely statement often quoted but of particular importance to air pollution considerations was made at the NATO World Meteorological Conference in 1986, which noted:

"We are conducting one giant experiment on a global scale by increasing the concentration of trace gases in the atmosphere without knowing the environmental consequences" [9].

The increasing rate of global energy use which is fueling increasingly rapid technological change is also unfortunately generating increased levels of air pollutants. While improvements in technology which require increased energy use are desirable and necessary especially in developing nations, the accompanying air pollution has resulted in increasing documented evidence of global, regional and local climate modifications including the warming 'greenhouse' effect, sulfuric and nitric acid rains, the formation of photochemically-produced ozone in smog, decreased levels of stratospheric ozone, increased air-borne particulates, decreased visibility, detrimental health effects, decreased agricultural productivity, and destruction of, and irreversible changes to, natural ecological systems [14].

Emissions of nitrogen oxides (NOx) produce nitric acid rains and lead to the production of ozone. Ozone is formed in smog when unburned hydrocarbons and nitrogen oxides mix in the presence of sunlight. Rains containing sulfuric and nitric acids result from burning of fossil and biomass fuels. Acidic atmospheres are found in the form of fogs, dry gases and particulates in all heavily urbanized areas. Lakes in California affected by acid rains now show acidic trends not apparent in the last 150 years [15]. Rains affected by mobile sources in urbanized areas of California have been measured as much as 300 times more acidic than those in natural unpolluted areas. Increasingly urban sprawl into rural areas less affected by air pollution is leading to long commutes as in Northern California where traffic within the County of Sacramento travels 37,000,000 km (23,000,000 mile) each day.

Acidic air has a high correlation with decreased health and is a major cause of asthmatic and bronchial respiratory events. Air quality in the South Coast Air Basin of Southern California currently exceeds Federal and State of California Ambient Air Quality Standards (AAQS). It has been estimated that improving air quality in the air basin to meet current AAQS would result in a savings from health benefits alone of $9.4 billion per year for Federal AAQS and $14.3 billion per year for California AAQS [16]. The air quality health study estimated that inland transport of coastal air basin emitted air pollutants if reduced to the AAQS would result in twice the above savings.

Increased air pollutants such as ozone result in significant losses in forestry and agricultural production. In the Central Valley of California elevated concentrations of ozone result in losses greater than 10% from very sensitive crops including rice, dry beans, grapes, onions, lemons and oranges. Sensitive crops with less than 10% loss include alfalfa, wheat, sweet corn and tomatoes. Typical crop production losses from ozone for grapes and cotton are estimated at 20% per year in California. It was estimated that for the whole of the U.S., ozone causes a $5 billion loss/yr to agriculture [17]. Studies of California's $14 billion/yr agricultural industry have estimated, using 1984 as a base year, that decreasing ozone levels to the State AAQS would yield a $332.9 million per year benefit in increased crop production.

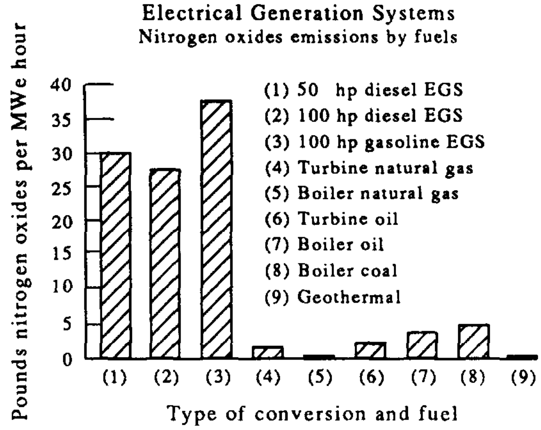

Fig. 2. EGS NOx emissions.

3.1. *Electrical Generation Systems' air-borne emissions comparison*

Air-borne emissions of NOx, SOx, PM, and C are compared in Figs 2–5 for EGS using internal combustion engines and turbines, external combustion boilers, and geothermal energy. Fuels considered include diesel, gasoline, natural gas, fuel oil and coal. Each EGS system utilized 'Best Available Control Technology' (BACT) for the particular installation. Each EGS was rated in terms of the emissions per Megawatt hour of electrical production (lb/MWe-hr).

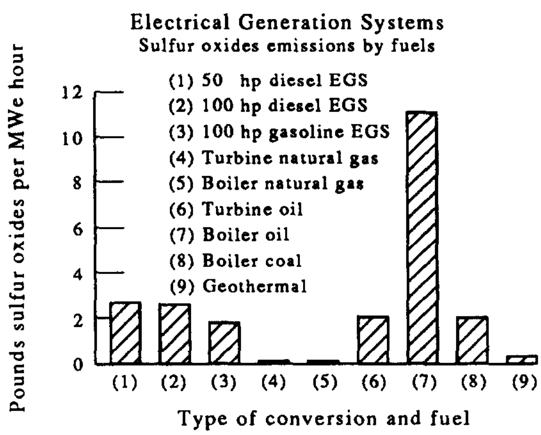

Fig. 3. EGS SOx emissions.

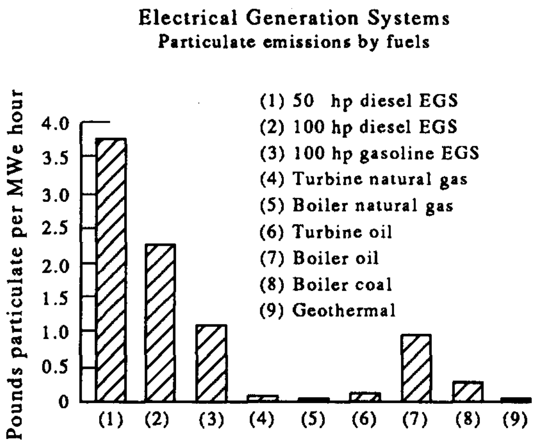

Fig. 4. EGS PM emissions.

USEPA BACT determinations are selected by considering, comparing and selecting the AECS with the lowest energy use, environmental and economic impacts for the particular installation.

The internal combustion engine examples used in the following section were selected from emissions factors compiled by the EPA [21]. Examples selected included typical small EGS 50 hp (37 kW) and 100 hp (75 kW) diesel engines, and a 100 hp (75 kW) gasoline engine. These are referred to in the figures as types (1), (2) and (3) respectively. The GE Frame 7 gas turbine examples type (4) using natural gas and type (6) using fuel oil were obtained from a BACT determination made by the North Carolina DEH Permit No. 6586R. The boiler example using natural gas type (5) was obtained from a determination made by the Bay Area Air Quality Management District, San Francisco. The boiler example burning fuel oil type (7) was taken from a BACT determination made by the Wisconsin DNR Permit No. 88-DLJ-024. The boiler example burning coal type (8) was taken from a BACT determination made by the Nevada DEP Permit No. 996 through 1007 [18]. The geothermal example has a typical permitted normal operation hydrogen sulfide (H_2S) air emissions limit of 100 grams per MWe hour (0.22 lb-H2S/MWe-hr) which is equivalent after atmospheric oxidation to a sulfur dioxide emission rate of 188 g-SOx/MWe-hr (0.41 lb-SOx/MWe-hr).

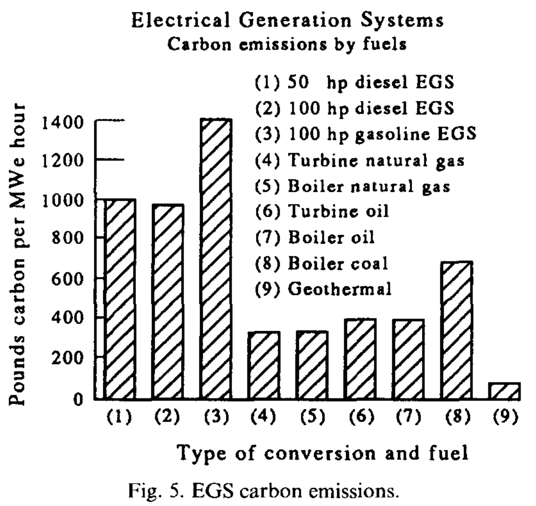

Fig. 5. EGS carbon emissions.

The comparison of NOx emissions from the selected EGS systems and fuels is shown in Fig. 2. Note that the emissions from diesel and gasoline internal combusion engine driven EGS types (1), (2) and (3) are considerably higher than either the gas turbine or the external combusion boilers. The higher compression ratios of internal combustion engines and the high internal temperatures both result in higher NOx emissions.

The comparison of SOx emissions from the selected EGS systems and fuels is shown in Fig. 3. SOx emissions are a direct function of the sulfur contained in the fuels and the degree to which the AECS reduces emissions. Typical sulfur contents of fuels are negligible for natural gas after processing, 0.04% for gasoline, 0.4% for diesel, 1% for fuel oil and 1 to 5% for coal. The diesel and gasoline engines powered EGS types (1), (2) and (3) are comparable to the gas turbine burning low sulfur oil (6) and the boiler burning coal with lime scrubbing (8). The boiler burning oil (7) was permitted using 1% sulfur oil. Low sulfur (<0.05%S) can be specified which would have lowered the SOx emissions of (7) by a half or more. Natural gas's negligible sulfur is evident for the gas turbine (4) and the boiler (5). Biomass EGS SOx emissions are dependent upon the sulfur content of fuel and are typically 0.5 lb-SOx/MWe-hr while WTE are typically 6 lb-SOx/MWe-hr. The equivalent SOx emissions for geothermal (9) are very low compared to fossil fuels excepting natural gas.

The comparison of PM emissions from the various EGS systems and fuels is shown in Fig. 4. Particulate emissions are a direct function of the burning efficiency of the EGS system, the amount of noncombustible inert materials in the fuels, the production of exhaust aerosols directly and from wet cooling towers, and the efficiency of the AECS. The selected diesel and gasoline engine powered EGS (1), (2) and (3) produce higher PM emissions than EGS systems running on natural gas (4) and (5), the turbine on oil (6) or the baghouse-scrubbed coal (8). The low PM emissions estimates of the Coso geothermal (9) include cooling tower drift. Typical biomass and WTE PM emissions are limited to about 1 lb-PM/MWe-hr.

The comparison of fuels' carbon (C) emissions from the selected EGS systems is shown in Fig. 5. The C emissions are a direct function of the fuel carbon content and the efficiency of conversion. A carbon content of 87.4% C for diesel fuel and 84.6% C for gasoline was used following work by Unnasch [6]. A carbon content of 72% C containing 22,750 Btu/lb was used for natural gas, 85% C and 18,300 Btu/lb for fuel oil, and 75% C and 11,500 Btu/lb for coal, following work by Gleick [19]. The inefficiencies of the small diesel engine and gasoline powered EGS (1), (2) and (3) produce higher C emissions per MWe-hr than the larger more efficient EGS systems while geothermal C emissions are the lowest at 8% of coal.

3.2. *Air toxic emissions, AECS hazardous materials use and wastes*

Emissions of air toxics are coming under increased review as they are linked to toxicological and adverse physiological effects. Low emissions of air toxics are associated with processed natural gas combustion. Fuel oil emissions contain reportable concentrations of arsenic, beryllium, cadmium, chromium, mercury, lead, nickel, selenium, vanadium and Volatile Organic Compound (VOC) emissions such as benzene. Coal air toxic emissions typically include 30 or more toxics and hazardous compounds, which include heavy metals, asbestos, silicates and radioactive emissions from ^{222}Rn. Geothermal air toxics typically include hydrogen sulfide, arsenic, mercury, ammonia, lead, benzene and ^{222}Rn.

Air toxics may accumulate in the AECS wastes and become concentrated to hazardous levels. The wastes must then be carefully handled and disposed of properly so that potable water supplies and other aspects of the ecology are not adversely affected.

Bottom ash residuals from coal burning typically amount to 0.64 kg-ash/MWe-hr (1.4 lb-ash/MWe-hr) with an additional collection of fly ash amounting to 5.0 kg-fly ash/MWe-hr (11 lb-fly ash/MWe-hr). For a recently proposed 2,000 MWe coal fired power plant the bottom and fly ash was estimated at 20,900,000 mton (23,100,000 tons) of waste over the 35 year expected project life, with potentially severe impacts to fish, wildlife and their habitat [5, 23]. All nations face expensive and necessary improvements in minimizing air toxics and managing EGS hazardous wastes.

4. WATER USE IMPACTS FOR EGS SYSTEMS

Competition for water sources is occurring globally with extremes occurring in areas such as California which is in a sixth year of drought. Ever increasing municipal and industrial needs for water accompany technological developments. Water is used at every stage in the production of fuels for EGS systems, and is continuously used as power plant make-up water in wet cooling towers, boilers and water cooled condensers.

Water use in power plant wet cooling towers is substantial and, except for most geothermal EGS, must be supplied to the facility in competition with other water users. Water use for coal fired EGS projects is estimated at 18 hectare-meter/MWe-yr (22 acre-ft/MWe-yr). Nuclear power plant fuel extraction and processing, construction and operation water use is estimated at 23 hectare-meter/MWe-yr (29 acre-ft/MWe-yr). Solar PV water used for manufacturing and cleaning is estimated at 0.84 acre-ft/MWe-yr [4]. Typical small biomass power plants in the 12.5 MWe range require 27 hectare-meter/MWe-yr (34 acre-ft/MWe-yr). Geothermal power plants using wet cooling towers use 80% of the condensated steam which amounts to an estimated 44 hectare-meter/MWe-yr (56 acre-ft/MWe-yr).

5. TECs OF EGS: SUMMARY AND CONCLUSIONS

The EGS TECs discussed demonstrate many of the environmental and resource factors which typical financial EGS cost planning may over-look. In order to rank the findings, a TEC index of each of the EGS discussed was developed which combined the capital and externality costs, the air-borne emissions, the land disturbance and the water use.

Wind energy EGS had the lowest TEC index followed by small hydro, solar thermal, solar photovoltaic, geothermal, biomass, nuclear, waste-to-energy, natural gas, oil and lastly coal. The TEC index ranking demonstrates that renewable energy sources such as wind, small hydro, solar and geothermal have relatively small environmental and financial impacts when they are compared to biomass, WTE and the fossil fuel TEC EGS. With this distinction comes siting problems for renewable EGS associated with having to account at the energy origin site for the majority of the environmental, resource and financial impacts.

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