LAHMEYER INTERNATIONAL

MINISTRY OF ELECTRICITY
THE REPUBLIC OF YEMEN

RENEWABLE ENERGY STRATEGY AND ACTION PLAN

TASK 1: RENEWABLE ENERGY RESOURCE ASSESSMENT
DRAFT REPORT

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List of Abbreviations

AC	Alternating Current
BGR	German Geological Institute
CAMA	Civil Aviation and Meteorological Service
CF	Capacity Factor
CSP	Concentrating Solar Power
DLR	German Aerospace Center
DNI	Direct Normal solar Irradiance
EPA	Environmental Protection Agency
ESCWA	Economic and Social Commission for Western Asia
ESMAP	Energy Sector Management and Assistance Program
EU	European Union
FAO	Food and Agriculture Organization (United Nations)
FLH	Full Load Hours
GHI	Global Horizontal solar Irradiance
GNP	Gross National Product
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
GoY	Government of Yemen
GPS	Global Positioning System
HDR	Hot Dry Rock
HH	Households
IEC	International Electricity Commission
LI	Lahmeyer International
LPG	Liquid Petroleum Gas
MENA	Middle East and North Africa
MoAI	Ministry of Agriculture and Irrigation
MoE	Ministry of Electricity
MoP	Ministry of Planning
MWE	Ministry of Water and Environment
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction

NPV	Net Present Value
NRECA	National Rural Electric Cooperative Association
O&M	Operations and Maintenance
ORC	Organic Rankine Cycle
PE	Primary Energy content
PEC	Public Energy Company
PM	Project Manager
PV	Photovoltaic
QM	Quality Management
R&D	Research and Development
RE	Renewable Energies
REIS	Renewable Energy Information System
RESAP	Renewable Energy Strategy and Action Plan
RET	Renewable Energy Technologies
SHS	Solar Home System
TA	Technical Assistance
WB	World Bank
WIS	Wind Information System
WISIS	Wind and Solar Information System
WMO	World Meteorology Organization
WWTP	Waste Water Treatment Plants
YMS	Yemen Meteorological Service

1 Executive Summary

The Ministry of Electricity (MoE) of the Republic of Yemen is currently implementing a series of studies under the GEF Rural Electrification and Renewable Energy Project. This study, Renewable Energy Strategy and Action Plan (RESAP), is one of the studies and with the main objective of promoting sustainable development and improving the standard of living of the rural population by providing affordable access to modern and clean energies.

The RESAP study consists of 3 main tasks: i) resource assessment, ii) formulation of the National Renewable Energy Strategy, and iii) development of an Action Plan to be pursued by the GOY for the next 10 years. This Task 1 report presents the potential of renewable energy resources in the Republic of Yemen that could be exploited for grid and off-grid electrification. Resources assessed in the study include wind, solar, geothermal, small hydropower and biomass energy resources. Development options were also outlined in the study.

1.1 Wind energy resources

A wind resource map was developed using a wind resource calculation using three-dimensional meso-scale atmospheric model KLIMM based on available data from Global Upper Air Climatic Atlas and CAMA. The available meteorological wind observation data as well as the data from the ongoing wind measurement campaign within the scope of the Wind Resource Assessment and Demonstration Project at Al Hodeidah and Al-Mocha were also used as input in the resource calculation.

Based on the wind resource map, the technical potential for wind power was calculated. The technical potential was estimated using a class II wind energy converter and the power curve of Vestas V52 with a hub height of 50 meters and rotor diameter of 52 meters was used. Also mountainous areas with more than 30% slope have been excluded.

Technically attractive sites in Yemen are those that could generate more than 3000 full load hours (FLH) or a capacity factor (CF) higher than 35 percent. Assuming that around 40 percent of the potential shown in the technical map can be used, preliminary estimates show that around 14,214 MW can be developed at these sites. Economically attractive sites are however those with more than 3500 full load hours (FLH) or a capacity factor (CF) of about 40 percent. A capacity of about 2,507 MW could be developed at these sites which could generate around 8,293 GWh of electricity per year. These results are however preliminary due to limited availability of long-term data.

Areas with high power concentration, e.g. high capacity factors and high full load hours, are located in the coastal plains, from the south of Hodiedah Governorate to Taiz, Lahej, Aden, and some part of Abyan, as well as mountain areas in Saadah and Amran, north of Sana'a, Dhamar, Al-Beida, and Al-Dhale'e. The coastal plains from central Hodiedah up to northern tip of Hajjah as well as Abyan and Shabwa have also good potential for wind power development.

1.2 Solar energy

The solar resource assessment used both ground-based solar measurement data and processed satellite data. Ground-based measurement data are from the Civil Aviation and Meteorological Authority (CAMA) while the satellite data are taken from HelioClim information system. Solar insolation maps were generated, and used to assess the gross theoretical potential.

The annual average solar insolation in Yemen ranges from 5.2 – 6.8 kWh/m^2/day. The Governorates of Al_Beida and Dhamar receive the highest annual average radiation levels at around 6.8 kWh/m^2/day. Neighbouring Governorates such as Amran (southern part), Sana'a, Ibb, Al-Dhale'e, and southern part of Marib have also very high insolation ranging from 6.6 – 6.7 kWh/m^2/day. Some areas from south of Hajjah Governorate down to Al Mahwit and Al Hodeidah as well as the capital city of Al Mahara Governorate have lowest levels of solar radiation ranging from 5.1 – 5.2 kWh/m^2/day. Most of the coastal areas, from Al Hodeidah, down to Taiz, Lahej, Abyan, Shabwa, Hadramout and to Al Mahara have average insolation levels ranging from 5.4 – 5.8 kWh/m^2/day. Insolation levels from Al Jowf, down to Marib, to the central part of Shabwa, and to the central part of Hadramout range from 6.0 – 6.3 kWh/m^2/day. Socotra island has, on average, very high annual average insolation at around 6.6 kWh/m^2/day.

December is the coldest month of the year in Yemen with insolation levels range from 4.4 – 6.0 kWh/m^2/day. From January, solar insolation increases gradually until it reaches the highest stage in May and June at around 7.0 – 7.7 kWh/m^2/day. Solar radiation levels quickly drop in July and August due to the arrival of the intertropical convergence zone but slightly increase in September. Solar radiation then gradually decreases until it reaches the minimum intensity in December. The same pattern exists in Socotra island, though the months with highest insolation levels start from March until May.

Prospective applications of solar energy technologies were identified in the study and their technical potential was estimated. These applications include solar home systems for both rural and urban applications, concentrating solar power to potentially boost capacities of existing steam and gas turbines, and solar water heaters for utilization in dwellings in the highland regions, hotels and hospitals. The resource assessment study estimated a technical potential for these applications to reach around 2210 MW.

1.3 Geothermal energy

Yemen is situated near three tectonic boundaries which are among the most active areas of the world. These are the Gulf of Aden, the Red Sea and the Eastern African Rift System. These three tectonic plates meet in a triple junction which result in high geothermal gradient, and subsequently geothermal energy potential. In the Red Sea region, geothermal gradients range from 40°C/km to 77°C/km. The worldwide geothermal gradient average is only at around 30 °C/km.

There are several geothermal springs and gas vents which are spread in continental Yemen. These springs are grouped into: i) springs emergences at high elevation (1000 – 2000 meters above sea level) inside the Yemen Trap Plateau, in a triangle delimited by Sana'a to the North, Damt to the Southeast and Ta'iz to the South; ii) spring emerging at elevations between 300 – 1300 meters located in the Lahj, Abyan and Shabwah region; iii) spring emergences at elevations ranging 200-400 meters along the Great West Escarpment bordering the Western edge of the Yemen Trap Plateau from North of Hajjah to Southwest of Ta'iz, and iv) thermal discharges of the Hadramaut region with spring locations near the coast at elevation below 1000 meters above sea level.

Geothermal resources of the country are classified into the following: i) low enthalphy resources (70-80°C) with good potential exist in the sedimentary cover areas, ii) low-medium enthalpy resources (80-120°C) under limited pressure exist in the methamorphic basement region, iii) medium enthalpy resources (100-140°C) are associated with the Western Yemen volcanic province, iv) high enthalpy potential in some regions such as the Dhamar area (presence of fumaroles), the high heat flow in the Red sea area and sedimentary cover springs (indications of deep temperature exceeding 150°C).

Among these, the fields that show high geothermal potential suitable for power generation exploitation are identified to be those situated in the areas of Al Lisi, Al Makhaya and Damt. Within this region, Dhamar has the highest potential due to the presence of steam vents (fumaroles) and hot ground water in a young volcanic field. Also, Dhamar is accessible and proximate to a national transmission network. The technical potential for this region is estimated by GeothermEx, Inc. to range between 125 – 250 MW.

The study evaluated the geothermal potential for other regions which cover mostly the former North Yemen and comprise around 27 percent of the total land area of the country. The study estimated the geothermal heat in place using a volume methodology. Information related to stratigraphy, density and heating capacity of rock layers as well as initial and reference temperatures were considered in the analysis. Among the rock layers, the Tawilah Sandstone layer appears to have the best conditions for geothermal development in Yemen. The recoverable power from this layer amounts to 28,500 MW. Each well dug into this layer could generate an electrical capacity of around 3 MW.

1.4 Small hydropower

Hydropower could be generated in Yemen from existing dams and water supply systems. Hydropower potential sites were identified in the study and their resource potential was assessed. Twenty dams in Sana'a region and Al-Mahwit Governorate were appraised in the study. Most of these dams store water for only a short period in a year. The study evaluated the power that can be generated in emptying the dam given the volume of stored water, head, and the area of the orifice for 12 hours operation per day. A total of more than 1 MW capacity could be technically installed in these dams but the day of operation is rather limited. Two dams, Bani Matar and Shahekl, could generate power up to 21 days while the rest have operating days ranging from 1 to 20. The resource assessment study concludes that it is not possible to generate power from the existing dams given the low availability of water and potential competition of water use from agriculture.

Most promising sites for small and micro hydropower development are the wadis of Yemen. Stream flows of most of the wadis in Yemen are however short-lived, and only a few have minor base flows that may be seasonal or permanent but only in a limited section of the channel. Wadi beds are dry most of the time, and infrequent run-off peaks quickly occur and disappear. Sites favourable for constructing hydraulic structures were identified in 21 major wadis and resource potential was estimated based on the site technical parameters. Nine sites were identified with higher power availability from 280 to 355 days and total installed capacity ranging from 11 – 30 MW could be technically feasible.

The development costs of hydraulic infrastructures in these sites were estimated to be high. Thus it is not financially feasible to develop the sites mainly for power generation. Multiple water-use projects, based on wide storage reservoirs and shared benefits, are possibly the most appropriate solutions. Drinking water supply, irrigation and hydro power, managed together in one installation, are perhaps the most convenient way. Households within the proximity of the proposed infrastructures were found to be thinly distributed. In addition to the development costs constraints, the cost of transporting electricity from many of these sites to the nearby villages could be enormous due to sparse distribution of households within the economic distance of the sites.

1.5 Biomass energy

Biomass energy resources were assessed in the study based on the energy conversion pathway framework. The biomass sources which could potentially generate energy services in Yemen include the following: energy crops, residuals from primary production in agriculture and animal husbandry, forestry biomass, municipal waste and waste water.

Currently no crops are grown in Yemen with the primary purpose of supplying fuel or energy. The only exemption is trees in woodlands, agro-forestry and forests are managed to provide also traditional fuels like fire wood and charcoal. Energy crops could be produced in Yemen, under rain fed as well as irrigated conditions. But given the limited availability of arable land, the scarcity of precipitation and surface as well as ground water resources opportunity costs will be much higher than the return from fuel or energy production.

Agricultural activities in Yemen are concentrated in the regions with sufficient precipitation, from the highlands and mountains, to the coastal plains and some groundwater-fed wadis. A national balance of crop residues is being carried out and results show an insufficient amount of biomass residuals available for energy purposes.

The biomass potential for power generation in Yemen is therefore limited. The potential for crop residues is negligible as well as for energy crops and forestry residues. The most viable option for energy generation is from animal wastes and municipal solid waste.

Wastes from animal husbandry offer some potential for energy generation. Dung production from cattle and other ruminants concentrates primarily in Hodeidah, Ibb, Taiz, Dhamar, Hajiah, and Hadramout governorates. The potential for generating biogas from animal wastes in family farms and large-scale farms were assessed in the study. The amount of animal dung generated from a typical family farm varies by governorate but the study results show that an average family farm could not generate sufficient amount of animal waste to sustain biogas production needed for cooking and lighting. In farms with large herds (with more than 400 heads), study results show that biogas generation from animal wastes could potentially support power generation.

Those with smaller herds, biogas can be produced to satisfy farm heating needs. Waste generated in poultry farms are found to sustain biogas production that can be used for lighting which could extend farms' feeding time.

Big cities generate solid wastes that could potentially sustain commercial power generation either by incineration or land fill gas. Sana'a, for example, generates more than 450 thousand tons of wastes per year. Solid wastes collected yearly in Aden, Taiz and Al-Hodeidah amount to more than 100 thousand tons. The study shows that the landfill sites in Sana'a could potentially generate 3 MW of power while those in Aden, Taiz and Al-Hodeidah, at around 1 MW each.

The potential for producing methane gas from municipal wastewaterr was also assessed in the study. At present, the sewage sludge generated from waste water treatment plants in Yemen are being used by farmers as fertilizer. Sana'a, Aden and Al-Hodeidah are the main sludge production centres with waste water capacities of more than 30,000 m^3 per year. Biogas that can be produced from the sewage sludge in all waste water treatment plants in Aden could generate around 0.53 MW, while those from Sana'a and Al-Hodeidah amount to 0.29 and 0.22 MW of power. The biogas generated from these centres is relatively small for power generation but substantial for other purposes such as heating, lighting and cooking.

1.6 Renewable energy development options

1.6.1 Grid-based Options

Wind, solar, geothermal and to some extent municipal solid waste are found to sustain commercial scale power generation in Yemen. The study outlined pipeline of projects that could be realistically developed given the right enabling environment in Yemen during the period 2010-2020 (Table 1-1).

These projects could be developed through public private partnerships but the first few projects such as the 10 MW wind, 5 MW geothermal, and 10 MW solar thermal could be implemented as pilot projects funded entirely by the public sector. Indicative investment costs and generation costs of these projects are shown in Table 1-2.

The study estimated investment requirements of the 511 MW pipeline of projects to be more than US$ 900 million (Table 1-3).

Table 1-1: Renewable energy power development 2010-2020.

Year	Wind (MW)	Geothermal (MW)	Solar (MW)	Landfill Gas (MW)	Total (MW)
2010	10 [1] (Mokha/Hodeidah)			3 [1] (Sana'a)	**13**
2011					
2012	100 (Aden/Mokha)		10 [1]	3 (Aden, Taiz, Hodeidah)	**113**
2013					
2014	100 (Aden/Mokha)	5 [1] (Dhamar)			**105**
2015			50		**50**
2016	50 (Mokha or Aden)				**50**
2017					
2018					
2019					
2020	80 (4 sites in Highlands)	50 (Dhamar)	50		**180**
Total	**340**	**55**	**110**	**6**	**511**

Note: [1] could be developed as pilot projects with public sector financing

Table 1-2: Pilot project investment and generation costs

	Investment Costs (US$ million)	Generation Costs (US$ cents/kWh)
10 MW Wind Power Plant	14.28 [1]	7.2
10 MW Solar Thermal Plant Without thermal storage With thermal storage	 24.5 47.8	 18.45 12.99
5 MW Geothermal Power Plant Binary Flash	 19.65 12.05	 5.60 3.24
3 MW Landfill Gas Power Plant	9.42	6.50

Note: [1] (7.14 x 2)

Table 1-3: Investment requirement of renewable energy project pipeline

Technology	Capacity (MW)	Capital Costs (million $/MW)	Investment Costs (million $)
Wind	340	1.6	544
Geothermal	55	2.0	110
Solar Thermal	110	2.45*	269.5
Landfill Gas	6	3.14	18.84
Total	511		942.34

* parabolic trough technology with thermal storage.

1.6.2 Off-grid options

Among renewable energy resources assessed in the study, solar energy is the only abundant resource in Yemen that could be exploited to provide energy services to rural and remote households and communities that could not be reached by grid extension.

Solar homes systems (SHS) are the most viable and appropriate options in most of these areas. A solar home system typically consists of a solar module consisting of an array of solar cells, and balance of system composed of electricity conditioning and/or controlling device such as inverter or regulator, electricity storage device such as battery (except in grid applications), and support structure and cabling connecting the power system to either the load or the grid.

SHS are within the class size range of 10 – 100 W of solar PV applications. These technologies are currently available in Yemen. Sizes available in the market are 40 W and 70 W.

The National Rural Electrification Strategy Study is being carried out in Yemen, and the study demarcates off-grid and grid-based areas. Another study, Market Study and Pipeline Development for Solar PV, is also being carried out in the country. The study undertakes solar PV market assessment and characterization, develops five replicable project pipelines, and provides broad design of technical details, investment requirements and institutional arrangements for the project.

1.7 Conclusion

The Republic of Yemen is endowed with significant amount of renewable energy resources. Resources with potential for large-scale exploitation include wind, solar and geothermal energies. To some extent, the energy conversion of municipal solid waste through landfill gas could potentially sustain commercial scale development (Table 1-4).

More than 500 MW of installed capacity consisting of more than 20 projects from wind, solar, geothermal and landfill gas could be potentially developed in the country given the right enabling environment between now and 2020. These projects could generate a total of more than US$ 900 million of capital investments in the country.

Similarly, solar PV applications could be used to provide energy services in the rural areas. Two separate studies, the National Rural Electrification Strategy Study, and Market Study and Pipeline Development for Solar PV, are being carried out in the country. The results of these studies would be the basis for determining the potential of solar energy resources in supplying electricity services in rural and remote communities in Yemen.

Table 1-4: Renewable energy resource potential in Yemen

Resources	Technical Potential
Wind energy	15,237 MW
Solar energy	average annual radiation 5.2 – 6.8 kWh/m^2/day *Identified applications* 53.2 MW (Solar home systems) 1,824 MW (Concentrating solar power) 332.7 MW (Solar water heating)
Geothermal	125-250 MW (Dhamar region) 28,500 MW (Other regions)
Small hydropower	11-30 MW
Biomass	7.53 MW (landfill gas) 1.04 MW (sewage sludge)

Task 2 of this study addresses the rationale why it is necessary to promote the utilization of grid and off-grid renewable energies in Yemen and formulates a national strategy to achieve the target 500 MW of renewable energy generation and the targeted volume of solar home systems to be distributed in rural areas. In addition, an action plan elaborating specific actions to be undertaken by the Government over the next ten years to support the realization of these goals will be covered in Task 3 of this study.

2 Wind Energy Resource Assessment

2.1 Wind Resource Assessment Methodology

2.1.1 Meso-scale Atmospheric Model

Wind resource assessment was undertaken in this study using the KLIMM model, a three dimensional numerical meso-scale model of the atmosphere. The model can simulate wind situations at any point in the atmosphere. With this model, an analysis of typical weather situations as well as locally measured wind resource data, the long-term annual wind speed for any location can be calculated.

Figure 2-1 shows the general simulation approach of KLIMM. As shown in the figure, KLIMM is a 'top-down' model. Starting from the distribution of the upper air geostrophic wind, the model calculates the wind direction and the wind velocity for each grid cell within the three-dimensional terrain.

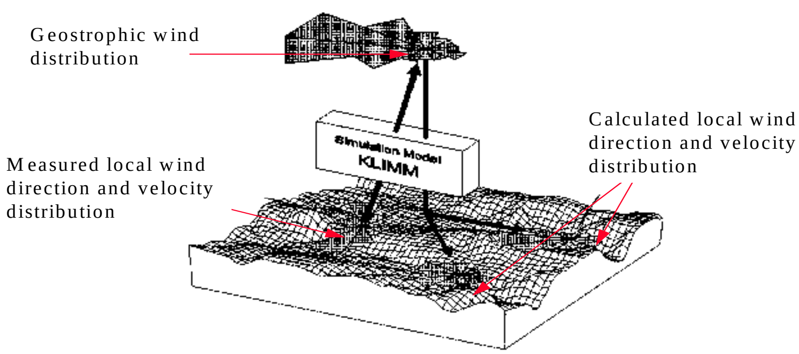


Figure 2-1: Simulation method of the model KLIMM

Data used in the model simulations are the following: i) geodetic height data (digital terrain model); ii) data of land-use (digital raster data); iii) information on the geostrophic wind conditions and air temperature stratification; iv) measured wind velocities at several wind measurement stations.

2.1.2 Topography and Land-Use Data

The Republic of Yemen is situated in the Middle East, bordering the Arabian Sea, Gulf of Aden and Red Sea between Oman and Saudi Arabia. Yemen covers an area of approximately 527,970 km^2 and is located between 42.53 degree to 52.98 degree East and 12.50 degree to 18.95 degree North and its area is covered by mountains and coastal plain in the western part, respectively (Figure 2-2).

Topographic data of Yemen used in the study were obtained from the NASA Shuttle Radar Topography mission in 2004 (3 arc second data) and from the gtopo 30 arc second data model from the U.S Geological Survey. A software module was developed (top_use_edit) to enable the huge data amount to be processed for the complete area of Yemen. The wind map developed in the study is based on 3 arc second data with an approximate resolution of 250 m per topographic grid cell.

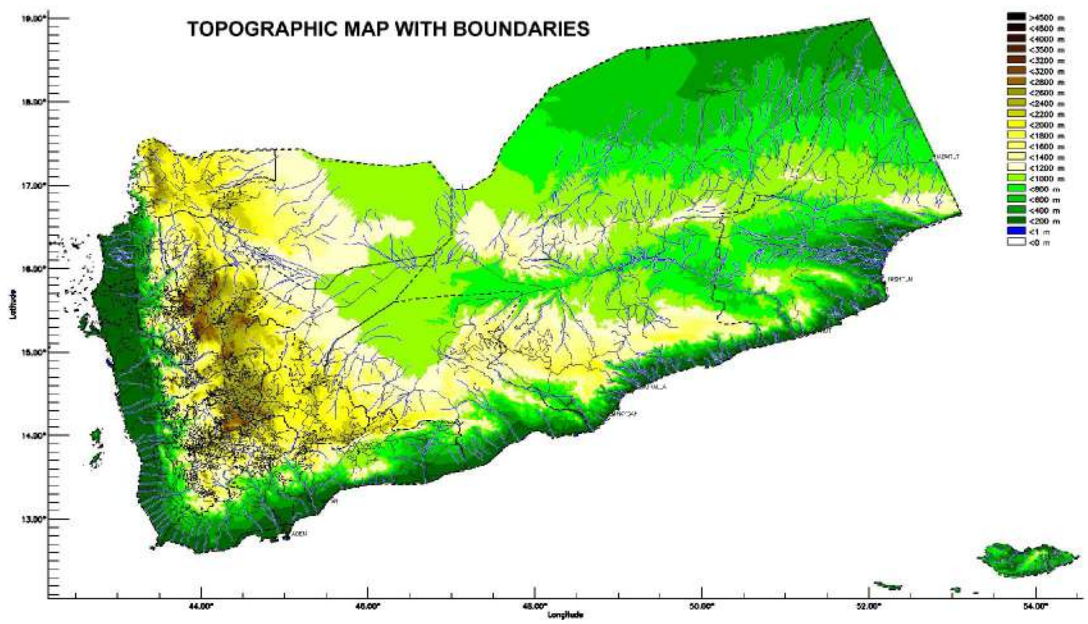


Figure 2-2: Digital elevation model (DEM) of Yemen

Land use data of Yemen from the NASA TERRA/MODIS HDF-EOS MOD12Q1 V004 products with a resolution of approximately 900 m per land use grid cell (30 arc second). Classification is available according to the classes shown in Table 2-1 and the land-use model for Yemen is shown in Table 2-3.

Table 2-1: Land use classification

0 – Water	10 – Grasslands
1 - Evergreen needleleaf forest	11 - Permanent wetlands
2 - Evergreen broadleaf forest	12 - Croplands
3 - Deciduous needleleaf forest	13 - Urban and Built –Up
4 - Decidous broadleaf forest	14 - Cropland/Natural Vegetation Mosaic
5 - Mixed forests	15 - Snow and Ice
6 - Closed shrubland	16 - Barren or sparsely vegetated
7 - Open shrublands	
8 - Woody savannas	
9 – Savannas	

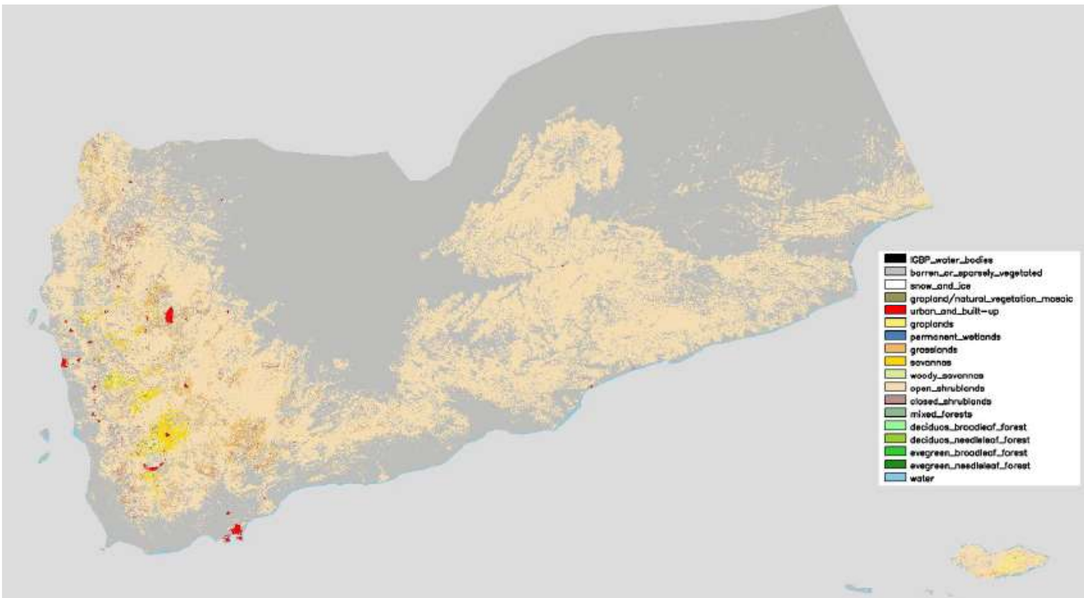


Figure 2-3: Digital land use model of Yemen

2.1.3 Upper Air Wind Data of Climatic Atlas

With regard to the wind direction and wind speed distributions to be expected in the investigation area, the upper air wind directions and wind speeds at a height of approximately 6,000 meters were taken from the Global Upper Air Climatic Atlas (Ver.1.0, April 1993). The data base, which was subject to this investigation, comprises a record period of 7 years with data from 1980 to 1987 and a period of 6 years from 1985 to 1991.

The average long- term representative upper air flow characteristic is shown in Table 2-2. The most frequent flow directions are represented by winds coming from north-eastern and eastern directions (> 50%/year). The same direction sectors are decisive for the higher wind velocities from the upper air.

Table 2-2: Mean upper air wind data

Sector	N	NE	E	SE	S	SW	W	NW
15.0 N 42.5 E, 500 mbar – approximately 5800 m								
[m/s]	*5.7*	*6.1*	*6.7*	5.1	4.5	4.4	5.6	5.3
[%]	*6.7*	*24.4*	*24.7*	9.0	5.6	7.9	13.4	7.9
15.0 N 45.0 E, 500 mbar – approximately 5800 m								
[m/s]	5.9	*6.4*	*6.9*	4.7	3.9	4.0	5.8	5.8
[%]	12.0	*28.5*	*19.2*	7.3	4.5	6.6	12.9	8.5
15.0 N 47.5 E, 500 mbar – approximately 5800 m								
[m/s]	*6.3*	*6.7*	*6.7*	5.1	3.9	4.6	6.0	5.9
[%]	*14.7*	*27.3*	*19.4*	6.8	4.1	6.7	12.5	8.3
15.0 N 50.0 E, 500 mbar – approximately 5800 m								
[m/s]	*6.2*	*7.0*	*7.0*	5.5	3.6	4.8	5.8	6.1
[%]	*13.7*	*28.4*	*20.3*	6.1	3.7	6.7	12.2	8.7
15.0 N 52.5 E, 500 mbar – approximately 5800 m								
[m/s]	6.0	*7.3*	*7.2*	5.2	4.4	5.1	6.4	6.2
[%]	12.1	*27.9*	*20.9*	6.3	3.9	6.7	12.3	9.7
17.5 N 50.0 E, 500 mbar – approximately 5800 m								
[m/s]	6.6	*6.8*	*6.4*	4.7	4.4	5.6	7.5	7.2
[%]	12.6	*23.5*	*15.3*	4.6	3.7	9.1	19.9	11.1
17.5 N 52.5 E, 500 mbar – approximately 5800 m								
[m/s]	6.4	*6.8*	*6.2*	4.8	4.5	6.1	*7.3*	6.9
[%]	10.8	*23.7*	*17.5*	4.2	3.9	8.3	*18.8*	12.2
12.5 N 42.5 E, 500 mbar – approximately 5800 m								
[m/s]	5.5	*6.4*	*7.6*	6.0	4.5	4.3	4.2	4.6
[%]	7.5	*27.3*	*34.3*	10.5	4.2	4.6	6.2	5.0
12.5 N 45.0 E, 500 mbar – approximately 5800 m								
[m/s]	5.5	*6.8*	*7.7*	5.5	3.9	3.9	*4.6*	4.7
[%]	10.4	*32.3*	*28.3*	8.3	3.6	4.1	*6.5*	6.2

* Prevailing frequency components are marked (*italic*)
Source: Global Upper Air Climatic Atlas, 1993

2.1.4 Upper Air Temperature Profile of Climatic Atlas

For the assessment of the wind characteristics in the investigation area, apart from the upper air wind statistics, information on the atmospheric temperature stratification are also required. The temperature stratification describes the strong influence of atmospheric stability on the local flow pattern. For instance, in a stable stratification of the atmosphere (represented by cold air near ground covered by warmer air in the upper layers) the vertical mixing of air masses – and the transportation of upper air wind speeds towards the ground – is very much suppressed compared to an atmosphere with unstable stratification (represented by air near ground warmer than above), which facilitates vertical mixing. As a consequence wind speeds at a certain location near ground can differ with atmospheric temperature stratification, although the upper air wind speed is the same.

Data are reported in the Global Upper Air Climatic Atlas (Ver.1.0, April 1993), providing extrapolated temperature profiles. Table 2-3 shows the long-term average temperature gradients for different height layers of the atmosphere.

Table 2-3: Mean values of upper air temperature data of climatic atlas

Pressure [mbar]/	Approximate Height [m]	15.0 N 42.5 E	Gradient [°C/100m]
500	5,800	-5.9	-0.63
700	3,100	11.8	-0.65
850	1,500	22.9	- 0.66
1,000	70	30.2	- 0.51

Source: Global Upper Air Climatic Atlas, 1993

2.1.5 Surface Measurement Data

Surface measurement data were taken from Civil Aviation and Meteorological Authority (CAMA) stations. Table 2-4 contains priority ranking of 5 available surface measurement stations for average wind velocity values measured at 10 m above ground. Table 2-5 shows the measured data from CAMA's Aden and Hodeidah stations.

All stations contain gaps in measurement series and the detailed environmental conditions (e.g. obstacles, roughness structure, condition of monitoring, exact location) are not known. The data are only available at 10 m measurement height and an observation interval of 1 hour. The stations of WMO and CAMA indicate different measurement results at 10 m hub height in the same area. Consequently the data indicate only a first estimate of the wind potential at local sites.

Table 2-4: Priority ranking of surface measurement stations (measuring height 10 meters above ground level.)

Ranking	Station 10 m above ground	E	N	Estimated Elevation [m.a.s.l]	Mean Wind velocity [m/s]
1	Hodeidah (CAMA/WMO)	45° 02'	12° 50'	12	9.2 / 7.0
2	Taiz	44° 08'	13° 41'	1385	6.6
3	Aden (CAMA/WMO)	45° 02'	12° 50'	3	6.5 / 7.2
4	Sana'a	44° 11'	15° 31'	2190	3.7
5	Ibb	44° 20'	14° 00'	1929	1.5

Source: CAMA

Table 2-5: Frequency distribution of Aden and Hodeidah station (A,k – weibull parameter)

Aden E 45° 02' N 12° 50' , 10 m height, mean: 7.2 m/s, A: 8.1 m/s, k: 2.8												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	7.2	5.3	6.9	7.4	7.4	7.5	7.3	7.9	8.1	6.4	6.2	5.3
f[%]	3.8	3.8	7.5	30.2	18.9	7.5	9.4	3.8	3.8	3.8	3.8	3.8
A[m/s]	8.1	6.0	7.7	8.3	8.2	8.4	8.2	8.9	9.1	7.3	7.0	5.9
k	2.8	2.2	2.6	3.1	3.1	3.1	2.5	2.3	2.7	2.0	2.2	1.6
Hodeidah E 45° 02' N 12° 50' , 10 m height, mean: 7.0 m/s, A: 7.9 m/s, k: 2.1												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	4.4	-	4.5	6.4	6.4	6.2	8.2	7.2	6.0	6.1	7.0	6.7
f[%]	4	-	4	4	4	4	33	13	7	18	4	4
A[m/s]	5.0	-	5.1	7.1	7.2	7.0	9.3	8.2	6.7	6.9	7.9	6.0
k	2.6	-	2.2	1.5	2.9	2.7	2.2	2.3	2.6	2.3	2.5	2.7

Source: CAMA

2.1.6 Reanalysed Wind Data at 2.5 Degree – Grid Nodes

To improve the accuracy of the calculation, the study reanalyzed the data of the World Wind Atlas at 50 meters height above the ground at the 2.5° - grid nodes covering Yemen to provide estimations of average wind velocity distributions in a series of grid nodes and improve the accuracy of the calculation. The results are shown in Table 2-6.

Table 2-6: NCEP / NCAR reanalyzed data

WA1, E 50 N 17.5 , 50 m height, mean: 5.5 m/s, A: 6.2 m/s, k: 2.4												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	5.3	5.1	4.7	4.3	4.6	5.5	**6.6**	**6.3**	5.1	4.1	3.9	4.5
f[%]	4.4	6.5	6.7	6.4	6.8	11.2	**22.8**	**17.4**	7.5	3.7	3.0	3.4
WA2, E 47.5 N 17.5, 50 m height, mean: 6.0 m/s, A: 6.7 m/s, k: 2.7												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	4.7	6.6	6.1	5.5	5.6	6.1	6.7	6.9	5.5	4.7	4.4	4.1
f[%]	2.8	8.0	11.7	11.0	9.5	10.3	13.1	18.2	7.8	3.4	2.4	1.9
WA3, E 45.0 N 17.5, 50 m height, mean: 5.1 m/s, A: 5.6 m/s, k: 2.5												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	4.4	5.0	5.5	5.0	5.0	5.1	5.0	5.2	5.2	5.4	4.9	4.4
f[%]	3.2	5.4	9.3	9.7	10.1	10.7	12.4	12.5	10.8	7.3	4.9	4.0
WA4, E 42.5 N 17.5, 50 m height, mean: 6.1 m/s, A: 6.8 m/s, k: 2.2												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	3.9	3.4	3.8	4.6	5.7	6.1	4.8	5.6	**6.1**	**7.5**	**7.5**	5.1

f[%]	4.6	3.3	3.2	5.1	7.5	8.1	4.6	6.9	**10.1**	**19.6**	**19.7**	7.5
WA5, E 50.0 N 15.0 , 50 m height, mean: 6.4 m/s, A: 7.1 m/s, k: 2.3												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	4.4	6.2	5.8	5.4	5.2	5.9	**6.3**	**8.3**	**7.6**	4.3	3.3	3.4
f[%]	1.0	2.3	5.3	9.1	13.7	17.2	**15.9**	**21.3**	**10.4**	2.4	1.0	0.6
WA6, E 47.5 N 15.0, 50 m height, mean: 6.2 m/s, A: 6.9 m/s, k:2.8												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	4.0	4.9	5.3	5.7	6.1	6.4	5.7	6.7	7.0	5.8	3.9	3.2
f[%]	0.8	1.7	3.4	7.3	18.1	24.7	13.5	12.6	11.9	4.2	1.0	0.7
WA7, E 45.0 N 15.0, 50 m height, mean: 5.5 m/s, A: 6.1 m/s, k: 2.8												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	3.1	2.8	4.8	5.2	**5.6**	**6.0**	**5.4**	5.3	5.7	5.4	5.0	4.2
f[%]	1.0	0.8	2.0	9.0	**20.2**	**19.3**	**10.7**	9.5	12.4	8.6	4.9	1.7
WA8, E 42.5 N 15.0, 50 m height, mean: 5.7 m/s, A: 6.4 m/s, k: 2.2												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	4.3	3.2	3.3	3.7	6.4	**6.5**	**5.6**	4.0	4.2	**5.5**	**6.9**	5.5
f[%]	2.9	1.8	1.5	2.3	9.9	**17.9**	**12.7**	7.2	7.4	**13.1**	**16.5**	6.9
WA9, E 50.0 N 12.5, 50 m height, mean: 6.6 m/s, A: 7.2 m/s, k: 2.2												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	3.4	5.5	6.5	5.9	4.8	4.5	5.8	**8.8**	**9.3**	5.3	3.3	3.0
F[%]	1.1	4.6	26.4	21.9	8.3	4.7	5.7	**14.6**	**10.3**	1.3	0.6	0.6
WA10, E 47.5 N 12.5, 50 m height, mean: 7.2 m/s, A: 8.0 m/s, k: 2.6												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	3.2	4.6	**7.4**	**6.9**	5.0	4.0	4.1	7.6	**9.5**	6.6	3.8	2.6
F[%]	0.5	1.2	**23.6**	**33.8**	7.4	2.4	1.8	7.4	**18.2**	2.8	0.6	0.4
WA11, E 45.0 N 12.5, 50 m height, mean: 7.0 m/s, A: 7.8 m/s, k: 3.2												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	2.9	3.7	6.8	**7.8**	6.0	3.9	4.4	7.1	**7.8**	6.0	3.9	3.3
f[%]	0.6	0.9	5.6	**43.4**	12.5	2.7	3.1	10.2	**14.8**	4.3	1.2	0.7
WA12, E 42.5 N 12.5, 50 m height, mean: 4.9, A: 5.4, k: 2.4												
Deg	0	30	60	90	120	150	180	210	240	270	300	330
v[m/s]	3.9	3.5	3.7	**5.8**	**6.0**	4.6	3.6	3.6	3.7	4.1	4.3	4.5
F[%]	2.7	2.2	2.7	**13.6**	**31.1**	13.1	6.3	6.0	6.7	6.8	5.0	3.8

2.1.7 Wind Map Calculation Procedure

With topography, land use, geostrophic wind distribution and the temperature stratification of the atmosphere the numerical model for the KLIMM flow simulations is well defined. For the defined model area, KLIMM runs are performed for totally 12 individual meteorological situations. Each individual flow simulation is carried out with the respective characteristic meteorological boundary conditions.

During the numerical calculation boundary conditions are kept fixed, while the three-dimensional flow pattern – after a certain iteration time – adapts itself within the complex terrain. The numerical iteration is proceeded until the wind speed alterations within one incremental time step under-runs a given limit value. The three-dimensional flow adjustments result in the occurrence of the characteristic flow patterns, such as channelling along valleys, speed-ups while traversing mountain ridges, weakening at the lee side of mountains and the large-scale passing of the major topographic structures.

For the preparation of the wind map the following working steps have been performed subsequently: i) data collection and pre-processing of input data for the KLIMM model, ii) performance of the flow simulations with the KLIMM model for totally 12 individual meteorological situations, iii) superposition of single results according to their individual frequency to give the complete representative annual wind pattern, iv) fine-adjustment of the long-term annual wind speeds through correlation with wind measurement data at locations within the investigation area; v) terrain following extraction of wind speeds for a fixed height above ground and preparation of wind map.

2.1.8 Model Area

The model area comprises a horizontal extension from 42.53 degree East to 52.98 degree East and 12.50 degree North to 18.95 degree north, covering an area of approximately 527,970 km^2 with a grid resolution of approximately 250 to 1000 meters for the wind map.

2.2 Wind Energy Potential

2.2.1 Mean Wind Speeds and Power Density

The spatial distribution of the annual mean wind speed at the height of 50 meters within the whole area of Yemen is shown in Figure 2-4.

Excellent wind conditions (wind speeds of above 7.5 m/s) are found in the coastal plains, from the south of Hodiedah Governorate to Taiz, Lahej, Aden, and some part of Abyan, as well as mountain areas in Saadah and Amran, north of Sana'a, Dhamar, Al-Beida, and Al-Dhale'e. The coastal plains from central Hodiedah up to northern tip of Hajjah as well as Abyan and Shabwa have also very good wind resources (between 6.2 – 7.5 m/s).

Power densities of the wind energy resource are shown in Figure 2-5. Regions mentioned earlier with very good to excellent wind conditions have power densities higher than 200 W/m^2. Power densities above this level are considered to be suitable for power development. Figure 2-5 clearly indicates the regions where wind resources could be potentially exploited for power development.

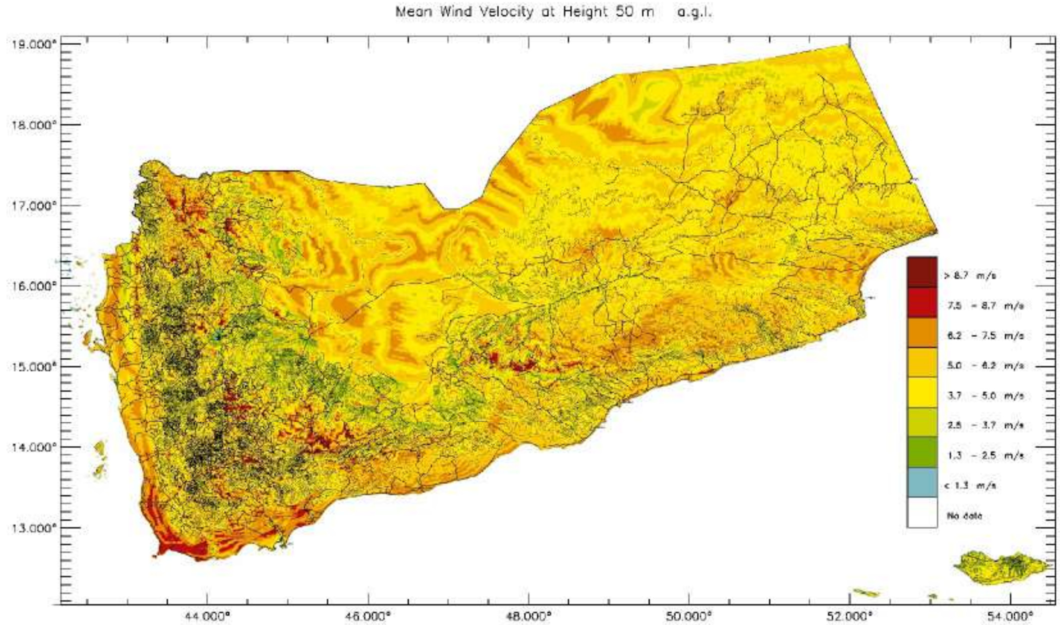


Figure 2-4: Average wind speed in Yemen (50 m above ground level)

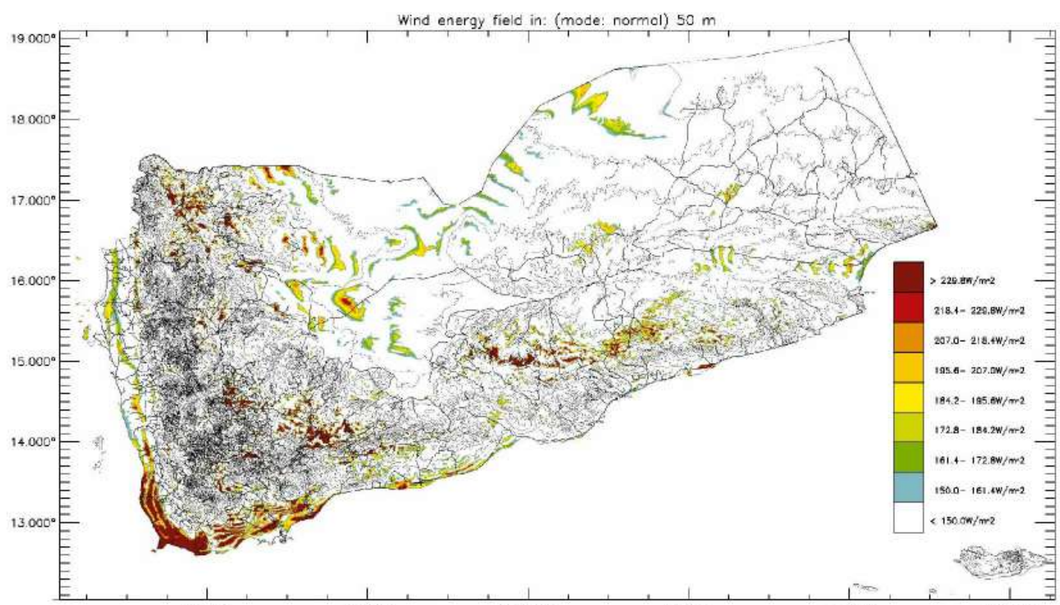


Figure 2-5: Wind power density (50 meters above ground level)

2.2.2 Technical and Economic Potential

The wind power technical potential was estimated in the study with the following assumptions:

- The calculation is based on a Class II wind energy converter: 52 meter rotor diameter, nominal rated power of 850 kW, and 50 meter hub height.
- The power curve of Vestas V52 turbine was used.
- The minimum theoretical power density considered is 150 W/m^2.
- Spacing of the wind energy converter is 10D – 5D, e.g. in main wind direction, the distance between the units is 10 x the rotor diameter D, and in cross wind direction, 5 x D.
- Mountainous areas with more than 30% of slope have been excluded
- No other exclusion areas (like settlements, infrastructure, reserves, etc have been factored out.

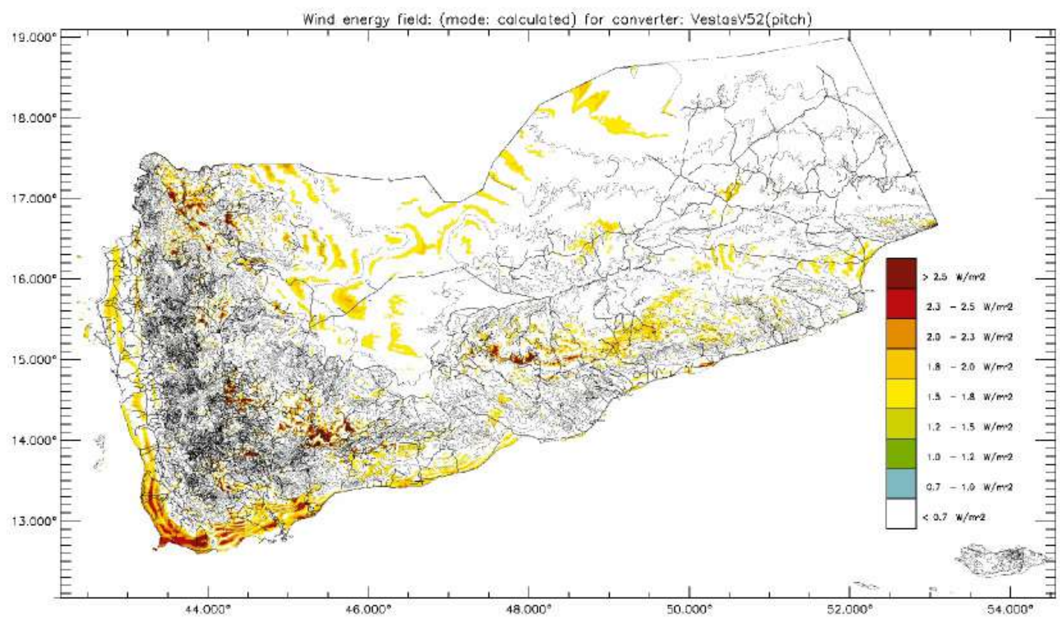


Figure 2-6: Technical wind energy potential

Figure 2-6 shows the spatial distribution of calculated power potential based on the above assumptions. It also presents regions with high power concentration, e.g. high capacity factors and full load hours. These include the coastal areas of southwest and southern part of Yemen, some specific locations in Sadaah, Sana'a, Dhamar, Al-Beidah, Taiz, and Hadramout. Calculated power densities in these areas are higher than 2.0 W/m^2. Areas with high power densities in the coastal plains could be easily identified and developed while those in the highlands with complex terrain needs further investigation and may require additional measurements.

The technical power density, W/m^2, represents the harvestable power in a given land area by a specified wind energy converter. Since turbines have constant spacing, this relates directly to the capacity factor and the number of full load hours (FLH) of operation per year. The relationship among these parameters is shown in Table 2-7.

Table 2-7: Relation between harvestable average power, CF and FLH

W/m2	CF	FLH
≤ 1,3	≤ 25%	2200
≤ 1,4	≤ 27%	2340
≤ 1,5	≤ 29%	2510
≤ 1,6	≤ 31%	2690
≤ 1,7	≤ 33%	2860
≤ 1,8	≤ 35%	3030
≤ 1,9	≤ 37%	3210
≤ 2	≤ 39%	3380
> 2	> 40%	3470

From Figure 2-6, assuming that only 40 percent of the potential can be used due to shading losses, settlement and exclusion areas, and considering only areas with capacity factors higher than 25 percent, one finds the total technical potential of 15,200 MW (Table 2-8). Taking into account best sites with capacity factors above 35 percent, the technical potential sums up to around 14,200 MW providing about 42,300 GWh of electricity per year.

Economically attractive areas are those with capacity factors of around 40 percent and full load hours of more than 3500 hours per year. This corresponds to more than 2500 MW of installed capacity with an average yearly electricity generation of around 8300 GWh.

As shown also in Figure 2-6, most of these economically attractive areas are situated in the coastal plains of Hodeidah (southern part), Taiz, Lahej, Aden and Abyan. Wind power development is also favourable in these areas due their proximity to the national grid.

Table 2-8: Wind power potential

FLH	MW installed	GWh/year
≤ 2200	115992	255183
2340	13	31
2510	0	0
2690	1024	2754
2860	8570	24511
3030	3137	9504
3210	1286	4129
3380	787	2662
> 3470	433	1503
Total (> 2200)	15237	43559
Total (> 3030)	14214	42308
Total (> 3470)	2507	8293

3 Solar Energy Resource Assessment

3.1 Solar Resource Assessment Methodology

The solar resource assessment used both ground-based solar measurement data and processed satellite data. Due to the irregularity of the available ground-based solar data, the study used the satellite data to build a long term series for mapping the time and spatial distribution on solar irradiation for Yemen. The actual measured ground based data was used to correlate with long-term data, and derive a correlation coefficient which indicates whether the ground-based data could be used to recalibrate the solar maps generated from satellite data. The maps were then used to assess the gross solar resource potential, and then with specific screening criteria, further narrow the gross potential estimates to a realistic technical and economic potential.

3.2 Solar Data Assessment

3.2.1 Satellite Data

The satellite data used in the study are taken from HelioClim information system. The satellite data consist of daily solar insolation measurements for the period 1985-2005. Daily irradiation values were derived from Meteosat satellite images and transformed into maps using the Heliosat methodology. The Heliosat method converts observations made by meteorological satellites into estimates of the global irradiation at ground level. The principle of the method is that a difference in global radiation perceived by the sensor aboard the satellite is only due to a change in apparent albedo, which is itself due to an increase of the radiation emitted by the atmosphere towards the sensor. A key parameter is the cloud index n, resulting from a comparison of what is observed by the sensor to what should be observed over that pixel if the sky were clear, which is related to the "clearness" of the atmosphere. In principle, it can be written as:

n t(i,j) = [ρ t(i,j) - ρ tg(i,j)] / [ρ tcloud - ρ tg(i,j))]

where

- r *t(i,j)* is the reflectance, or apparent albedo, observed by the spaceborne sensor for the time *t* and the pixel *(i, j)*: r *t(i,j) = p Lt(i,j)I0met e(t) cos qS(t,i,j)* , where *Lt(i,j)* is the observed radiance,
- r *t cloud(i,j)* is the apparent albedo over the brightest clouds, and
- r *t g(i,j)* is the apparent albedo over the ground under clear skies.

If the sky is clear, the apparent albedo r *t(i,j)* is close to the apparent albedo over the ground and the cloud index *n* is close to 0 (possibly negative). If the sky is overcast, the cloud index *n* is close to 1 (possibly larger). In brief, the cloud index *n* may be considered as describing the attenuation of the atmosphere (1 minus the transmittance). Thus, the cloud index *n* is a very convenient tool to exploit satellite images.

3.2.2 Ground-based Data

Ground based data was provided by Yemen Meteorological Service (YMS) from seven meteorological stations throughout the country (Table 3-1). The data presents daily average insolation values for various months between 1984 and 2000. The available ground-based data is highly irregular. For some years, measured data are only for 2 to 3 months. In most cases, at least one month data is missing in a year. For some stations, measurements were carried out only in the late 1980s while for some in the late 1990s.

Table 3-1: CAMA/YMS Meteorological Stations

Station Name	Location Indicator	Station index Number	Latitude(N)	Longitude (E)	Altitude (Meters)	Type of Records
SANA'A	OYSN	41404	′31 °15	′11 °44	2190	S/W
TAIZ	OYTZ	41466	′41 °13	′08 °44	1385	S/W
HODEIDAH	OYHD	41431	′45 °14	′59 °42	11.5	S/W
MARIB	OYMB	41407	′26 °15	′20 °45	1070	S/W
ALHAZM	OYJA	41393	′09 °16	′47 °44	1070	S
DHAMAR	OYDM	41434	′35 °14	′25 °44	2425	S
IBB	OYIB	41452	′00 °14	′20 °44	1929	S/W

Source: CAMA

3.2.3 Correlation between Ground-based Data and Satellite Data

A correlation analysis was made between the acquired satellite data and ground-based solar data in Yemen. The results are shown in Table 3-2. The poor correlation result was not entirely unexpected since the data are patchy and insufficient. In order to complete a valid and reliable correlation analysis, sample populations must have at least 5000 comparable entries. In the case of the ground-based data sets for the meteorological stations numbered, in most cases, only in the hundreds, which do not permit a dependable result. The low correlation result indicates insufficient and incomplete ground-based data.

Table 3-2: Correlation results (satellite data vs. ground measurements)

Met Station	Standard deviation	Mean Std deviation	Correlation coefficient
Dhamar	1.4934	1.22368	0.2673
Hasm	0.9897	0.7491	0.5215
Hodeida	0.8924	0.6040	0.5810
Ibb	1.1946	0.8765	0.3806
Sana'a	1.2320	0.9531	0.3742
Taiz	1.2660	0.9832	0.4345

Given the low correlation between the two individual sets of data, a correlation analysis was made for the ground based data set between the individual measurement stations. And although a correlation analysis between locations far removed does not generally produce a valid coefficient, due to the natural geographic variation in insolation, it does reveal some level of consistency in the data where a high correlation exists. This is a standard check where the quality of the data sets themselves is in question.

It can be seen that there is an emerging trend towards a positive correlation factor, for the stations relatively close to one another and with rising sample populations (Table 3-3), which goes some way to validate the data, nevertheless, overall, the data sets were inadequate to calibrate the resource atlas.

Table 3-3: Correlation results between meteorological stations

Measurement Stn 1	Measurement Stn 2	Number of Samples	Correlation Coefficient
Damar	Hasm	471	0.284765
Damar	Hodeida	437	0.109543
Damar	Ibb	437	0.109543
Damar	Sanaa	434	0.304749
Damar	Taiz	455	0.323113
Hasm	Hodeida	570	0.508157
Hasm	Ibb	570	0.508157
Hasm	Sanaa	557	0.653431
Hasm	Taiz	585	0.418858
Hodeida	Ibb	871	0.980105
Hodeida	Sanaa	799	0.687879
Hodeida	Taiz	818	0.641311
Ibb	Sanaa	1261	0.874832
Ibb	Taiz	1260	0.726503
Sanaa	Taiz	1723	0.737852

3.3 Solar Insolation

The annual average solar insolation in Yemen ranges from 5.2 – 6.8 kWh/m^2/day. Figure 3-1 shows the annual average insolation levels in Yemen. The Governorates of Al_Beida and Dhamar receive the highest annual average radiation levels at around 6.8 kWh/m^2/day. Neighbouring Governorates such as Amran (southern part), Sana'a, Ibb, Al-Dhale'e, and southern part of Marib have also very high insolation ranging from 6.6 – 6.7 kWh/m^2/day. Some areas from south of Hajjah Governorate down to Al Mahwit and Al Hodeidah as well as the capital city of Al Mahara Governorate have lowest levels of solar radiation ranging from 5.1 – 5.2 kWh/m^2/day.

Most of the coastal areas, from Al Hodeidah, down to Taiz, Lahej, Abyan, Shabwa, Hadramout and to Al Mahara have average insolation levels ranging from 5.4 – 5.8 kWh/m^2/day. Insolation levels from Al Jowf, down to Marib, to the central part of Shabwa, and to the central part of Hadramout range from 6.0 – 6.3 kWh/m^2/day.

Socotra island has, on average, very high annual average insolation at around 6.6 kWh/m^2/day.

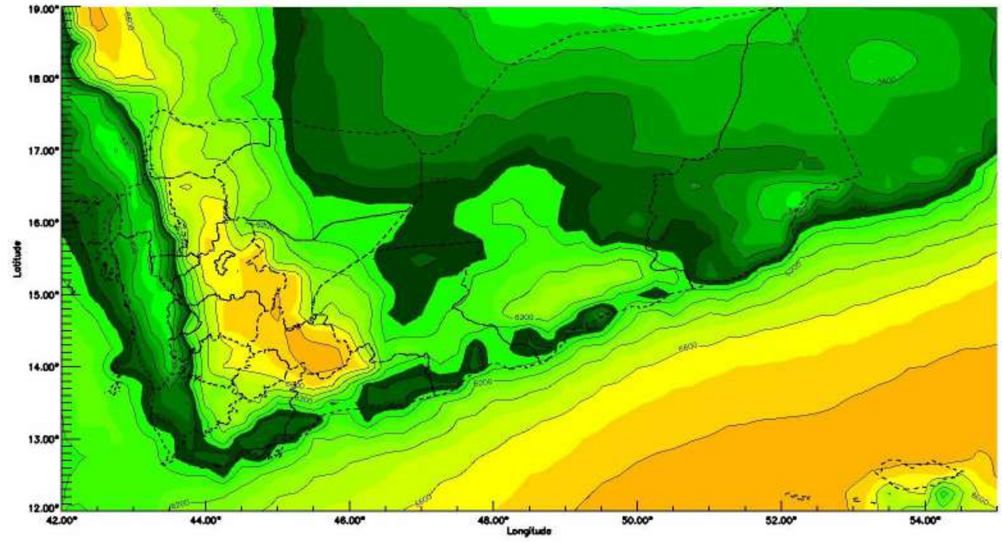


Figure 3-1: Annual Average Solar Insolation Atlas

Table 3-4: Average Solar Insolation

Month	Insolation Levels (kWh/m^2/day)		
	Mainland		Socotra Island
	High	Low	
Average	6.6 – 6.8	5.2 – 5.4	6.6
January	6.0 – 6.2	4.1 – 4.6	5.6
February	6.4 – 6.7	4.2 – 4.6	6.6
March	6.6 – 7.2	4.8 – 5.2	7.3
April	6.6 – 7.3	5.5 – 5.8	7.5
May	7.0 – 7.7	5.9 – 6.2	7.4
June	7.0 – 7.5	5.4 – 5.8	7.0
July	6.4 – 6.6	4.8 – 5.4	7.0
August	6.2 – 6.6	4.5 – 5.0	7.0
September	6.6 – 6-9	4.8 – 5.2	7.1
October	6.6 – 7.0	5.3 – 5.6	6.6
November	6.4 – 6.5	5.0 – 5.2	5.9
December	5.8 – 6.0	4.4 – 4.6	5.4

The monthly average insolation is summarized in Table 3-4. December and January have the lowest insolation levels. From January, the insolation increases gradually until it reaches the highest stage in May and June. The solar radiation levels quickly drop in July and August but slightly increase in September. From then it gradually decreases until it reaches the minimum intensity in December. The same pattern exists in Socotra island, though the months with highest insolation levels start from March until May.

The seasonal climate variation clearly affects the pattern of insolation levels. The Red Sea Convergence Zone occurs during March to May and mostly affects the western part of the country. This explains why the highest levels in Socotra island occurs earlier than the mainland. The monsoonal Inter Tropical Convergence Zone reaches Yemen from July to September. During this time, the moist air coming from the Indian Ocean converges with the dry air from the north. This explains the slight drop of solar insolation in July and August. A stable dry weather with few or no clouds starts from October to March.

Selected insolation atlas for selected months is shown in Figure 3-2, Figure 3-3, Figure 3-4, Figure 3-5, and Figure 3-6.

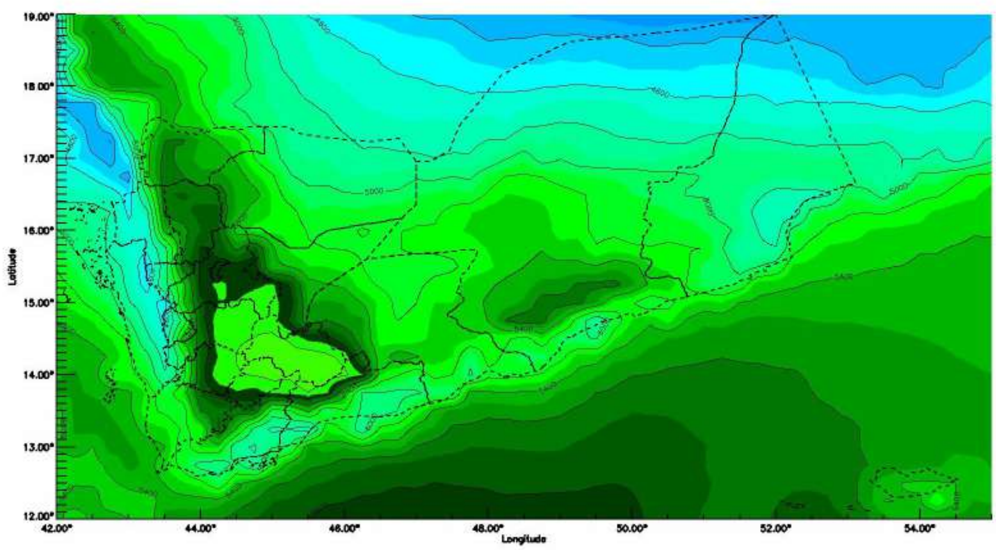


Figure 3-2: Solar Insolation Atlas for December

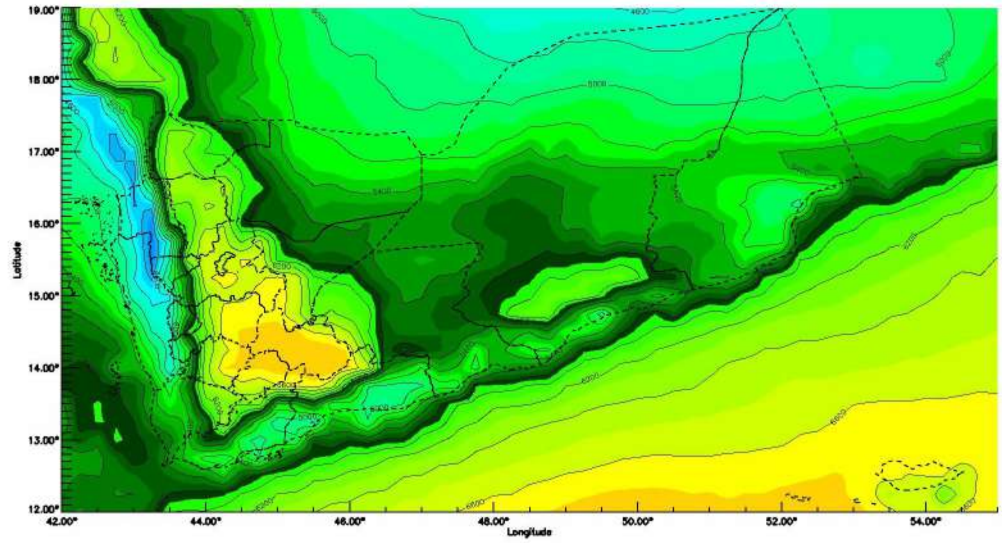


Figure 3-3: Solar Insolation Atlas for February

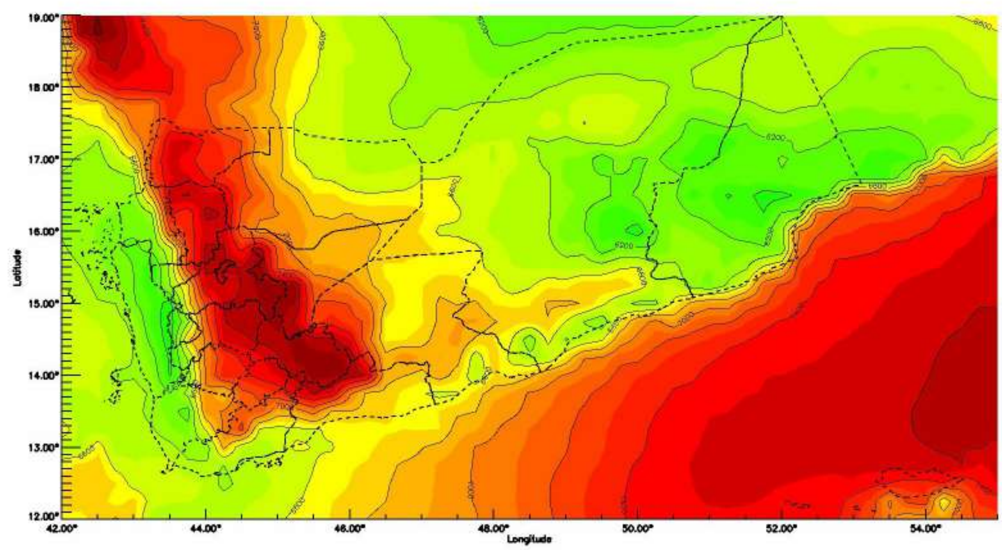


Figure 3-4: Solar Insolation Atlas for May

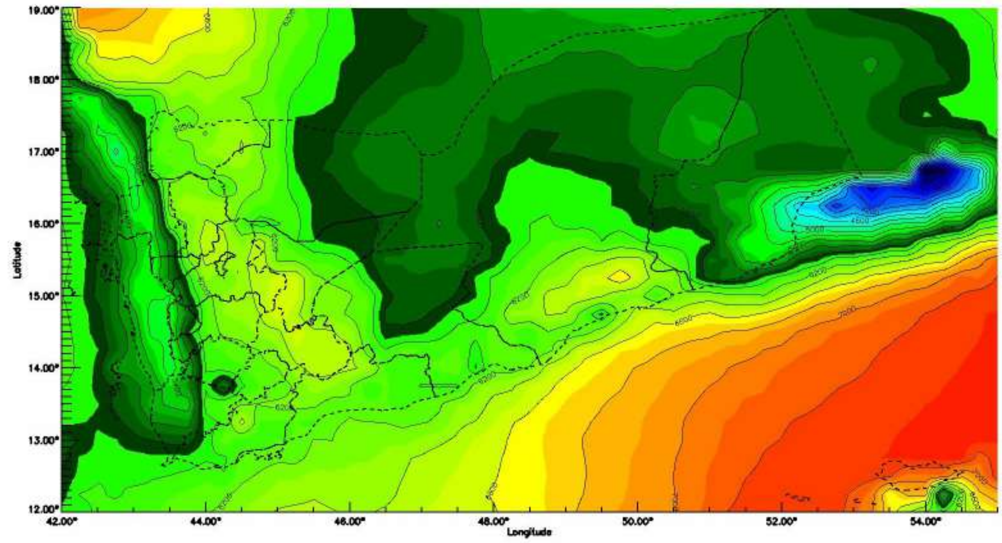


Figure 3-5: Solar Insolation Atlas for August

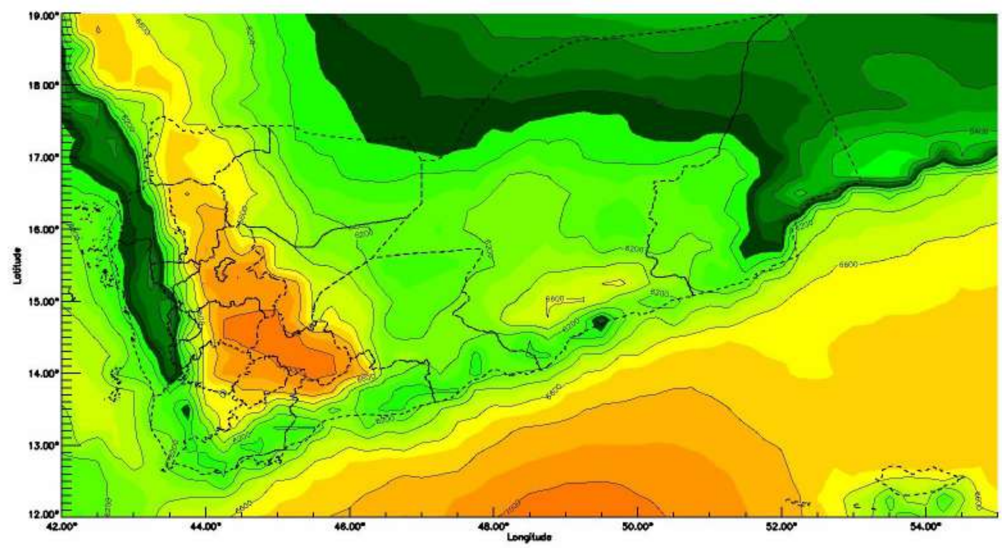


Figure 3-6: Solar Insolation Atlas for October

In addition to high insolation levels, the availability of solar radiation is also high in Yemen. The average sunshine hours in the country, based on CAMA's ground measurements, ranges from 7.3 hours per day in Sadarah to 9.1 hours per day in Socotra Island (Table 3-5). Sana'a has a daily average sunshine hours of 7.7.

The longer average sunshine hours signifies high energy production from solar energy technologies over the year. Thus, various energy services in the economy could be potentially satisfied by solar energy technologies. Also during the coldest period of the year (October to February), the average sunshine hours is over 8 hours per day. The high availability of solar energy during this period represents an important opportunity for solar heating applications in the country.

Table 3-5: Average Daily Sunshine Hours

	Al-Cood	Al-Abus	Hodeida	Lahj	Sana'a	Saiun	Sadarah	Socotrah	Taiz
Jan	7.6	8.8	8.9	7.1	8.5	7.5	5.1	8.7	7.7
Feb	8.4	7.3	9.1	6.9	7.0	8.7	5.4	9.9	8.7
March	8.3	8.2	7.2	8.0	9.0	9.2	7.2	10.3	9.1
Apr	8.5	7.8	9.1	8.6	6.9	8.7	9.0	10.8	9.3
May	9.9	9.2	8.8	9.1	9.0	10.0	8.6	9.0	9.0
Jun	7.9	7.8	7.6	7.6	7.5	8.8	8.4	7.8	7.8
Jul	7.8	7.2	7.1	7.2	5.9	7.8	8.8	9.2	6.4
Aug	8.2	7.5	6.6	7.8	6.5	7.9	8.2	7.2	7.2
Sept	8.3	6.9	8.0	8.3	7.4	9.2	8.0	9.7	7.5
Oct	9.7	8.3	9.9	9.0	9.3	9.5	7.2	9.6	9.3
Nov	10.1	8.0	10.0	9.3	9.2	9.2	6.5	8.9	9.1
Dec	8.3	7.9	9.1	8.1	7.1	8.7	5.4	8.7	8.8
Ave	**8.6**	**7.8**	**8.4**	**8.0**	**7.7**	**8.7**	**7.3**	**9.1**	**8.3**

Source: CAMA

3.4 Gross Theoretical Potential

The gross potential of Yemen's solar resource (i.e. the potential unconstrained by technical, economic or environmental parameters) can be described as varying over a range of approximately 5.2 – 6.8 $kWh/m^2/day$ over the land surface of 527,970 km^2. The gross theoretical potential was estimated by taking into account the disaggregation of the land area receiving increasing levels of insolation and an assumption of an efficiency of a solar energy conversion system. Table 3-6 shows that with an efficiency of 10 %, the gross potential could reach as high as over 110 million MW.

Table 3-6: Gross Theoretical Potential

Insolation ($kWh/m^2/day$)	Area (km^2)	Percent Land Area (%)	Gross theoretical potential* (Million MW)
< 5.2	243	0.05	0.05
5.2 – 5.4	30744	5.82	5.95
5.4 – 5.6	96640	18.30	19.40
5.6 – 5.8	93292	17.67	19.41
5.8 – 6.0	121655	23.04	26.20
6.0 – 6.2	61160	11.58	13.62
6.2 – 6.4	45474	8.61	10.46
6.4 – 6.6	32470	6.15	7.70
6.6 – 6.8	40823	7.73	9.98
> 6.8	5470	1.04	1.36
Total	527970	100.00	114.12

*assumes 10% system efficiency

3.5 Technical Potential

The gross theoretical potential, although a good indicator of solar resources, tends to overestimate actual electricity generation capacity. In developed economies, “technical” potential is defined as that potential, unconstrained by economic or environmental parameters. To estimate a more realistic technical potential, certain assumptions must be made. First, a technical evaluation of solar resources will have to balance between the implementation of the respective solar technologies. For example concentrated solar power (CSP) technologies have a system efficiency of around 20 percent (or if installed as a co-generation of electricity and process heat concept, the primary energy input is used with efficiencies of up to 85 percent), and PV based systems are typically assumed to have 10 percent system efficiency. Again this is different for solar thermal hot water systems, where efficiencies of 70 percent are common.

In addition, the technical potential assumes solar energy technology systems are used only where practical. Consequently, the technical potential discounts, or filters out, locations where solar is impractical. For example, areas excluded from the technical potential include forests (due to shading), agricultural lands, areas with sensitive habitats, and regions with north slopes greater than five percent. Commonly, technical potential is associated with locating PV systems on residential rooftops or commercial buildings, with CSP and other solar thermal power technologies considered separately.

3.5.1 Solar Home Systems

Solar home systems (SHS) are well-known and reliable option for bringing power to people living in remote areas, where grid extension or the construction of hybrid systems is not viable.

Basically, those systems are composed of a small solar array (1 or 2 modules), a solar battery, a simple regulator and electric appliances. They are mostly designed to provide power for lighting and information purposes (radio or TV). Other more energy consuming applications (grinding, welding, etc.) cannot be supplied by such systems.

SHS are very suitable for Yemen, as many small communities live too far from the main grid, or rural isolated grids, to hope to be connected to them in the mid-term future. Such systems will allow people to benefit from clean and reliable sources of energy. SHS are a great energy supply option to provide power to remote communities or small villages, where grid connection is not interesting in terms of costs. This option is usually much more cost-effective.

Potentially, all un-electrified households in Yemen could be served through solar PV dissemination. Currently, there are more than 1 million households without access to electricity (Table 3-7).

Table 3-7: National Electricity Access

	Urban		Rural		All	
	# of HH	%	# of HH	%	# of HH	%
PEC national grid	0	0.0	56,988	3.3	56,988	2.5
PEC isolated system	21,118	4.2	31,927	1.8	53,045	2.4
Cooperative	0	0.0	2,328	0.1	2,328	0.1
Private	22,603	4.4	157,414	9.0	180,017	8.0
Village/community	12,642	2.5	26,771	1.5	39,413	1.8
Relative/neighbour	6,311	1.2	52,484	3.0	58,795	2.6
Family-owned	0	0.0	6,724	0.4	6,724	0.3
Other	62,674	12.3	334,636	19.2	397,310	17.7
Total non-grid	465,421	91.6	735,359	42.2	1,200,781	53.4
HH with no access	42,665	8.4	1,005,727	57.8	1,048,392	46.6
Total HH	508,086	100.0	1,741,087	100.0	2,249,173	100.0

Source: ESMAP, 2005

The technical potential for solar home systems is estimated based on the dissemination of two SHS options: a typical 75 Wp for urban areas, and a 40 Wp mini SHS for rural regions. This is in line with the proposed SHS dissemination program to be developed by IT Power.

Given these assumptions, 3.2 MW could be deployed in urban areas, and another 50 MW in the rural areas. In reality, the 3.2 MW of capacity deployed in urban areas will, most likely, be met by grid extension (Table 3-8). However, this does not exclude the aforementioned load from being met by solar, as there exist a substantial potential for other solar energy technologies.

Table 3-8: Solar home system technical potential

	No of HH	System Size	**Technical Potential (MW)**
Rural	1,005,727	40 Wp	**40.2**
Urban	42,665	75 Wp	**3.2**
Total			**43.4**

3.5.2 Concentrating Solar Power

Solar thermal power plants, often also called Concentrating Solar Power (CSP) plants, produce electricity in much the same way as conventional power stations. The difference is that they obtain their energy input by concentrating solar radiation and converting it to high-temperature steam or gas to drive a turbine or motor engine.

Four main elements are required: a concentrator, a receiver, some form of transport media or storage, and power conversion. Many different types of systems are possible, including combinations with other renewable and non-renewable technologies, but the three most promising solar thermal technologies are: parabolic trough, parabolic dish, and power tower. Parabolic trough plants are currently the most mature CSP technology.

Parabolic trough-shaped mirror reflectors are used to concentrate sunlight on to thermally efficient receiver tubes placed in the trough's focal line. A thermal transfer fluid, such as synthetic thermal oil, is circulated in these tubes. Heated to approximately 400°C by the concentrated sun's rays, this oil is then pumped through a series of heat exchangers to produce superheated steam. The steam is converted to electrical energy in a conventional steam turbine generator, which can either be part of a conventional steam cycle or integrated into a combined steam and gas turbine cycle.

The CSP resource assessment for Yemen is already available from the German Aerospace Centre (DLR), as an output of the MENA-CSP study to achieve sustainable long-term energy and water security in the EU-MENA region.

Solar electricity potentials were calculated from the annual direct normal radiation with a conversion factor of 4.5%, which takes into account an average annual efficiency of 15 % and a land use factor of 30 % for CSP technology. Exclusion areas like urban and industrial use, hydrography, protected areas, land cover, geomorphology and topography were also considered.

One finds that Yemen has a total technical potential of around 5143 TWh per year. 3000 TWh are at sites with at least 2400 kWh/m²a of direct normal radiation and thus are highly attractive for commercial development. Using a parabolic trough technology with capacity factor of 24 percent, the technical potential translates to 2446 GW and the potential for commercial development to 1426 GW of electrical power (Table 3-9).

The most practical utilization of CSP for power generation is to run in parallel with gas-fired combined cycle plants. This will allow a step wise approach for CSP integration, along with support of existing systems. Natural gas-based power plants being constructed and planned in Yemen, however, are mainly gas turbines and not combined cycle power plants (Table 3-10). But this could be upgraded to combined cycle and CSP could be integrated in the second stage turbine. Another alternative option for CSP is to run in parallel with the existing steam turbine power plants in Ras Katnib, Mukha, Hiswa and Hiswa-2.

Table 3-9: Technical Potential Calculation

Technical Potential = 5143 TWh/year

Economic Potential = 3000 TWh/year

Coastal Potential = 390 TWh/year (< 200 m above sea level)

Using Parabolic Trough Technology

Technical Potential = 2446 GW

Economic Potential = 1426 GW

Coastal Potential = 186 GW

$E_{CSP} = P_{CSP} \cdot CF_{CSP} \cdot 8760$

E_{CSP}	Annual electricity yield, MWh/y
CF_{CSP}	Capacity factor as function of load; 24% for parabolic trough technology
P_{CSP}	Installed capacity [MW]
8760	represents the total hours per year

Source: German Aerospace Centre, 2005

Table 3-10: Steam and Gas Power Generation Plants

	Name of Power Plant	Number of units	Date of Commissioning	Installed Power	Generator rated power	Max.Power Output at Generator Terminal (de rated due to age of unit) [MW]					
				[MW]	[MVA]	2005	2007	2008	2013	2018	2025
Steam	RAS KATNIB	5	existing	150	188	140	140	140	*140*		
Steam	MUKHA	4	existing	160	200	138	138	138	*138*		
Steam	HISWA	5	existing	125	156	110	110	110	*110*		
Steam	HISWA-2	1	2007	60	75		60	60	60		
	Subtotal Steam			495	619	388	448	448	448		
Gas	Marib 1	4	as of 2007	452	565		339	339	339	339	452
Gas	Marib 2	4	2008	452	565			452	452	452	452
Gas	Mabar 1	4	as of 2010	352	440				*352*	352	352
Gas	Mabar 2	4	as of 2016	352	440					352	352
Gas	Aden	7	as of 2013	735	919				*125*	500	875
Gas	Hodeidah	5	as of 2014	315	394					*250*	*625*
	Subtotal gas			2658	3323		339	791	1268	2245	3108

Source: Marib Power Project 2^{nd} Stage

The steam power plants are planned to be de-commissioned in 2013 but the recent review of the power generation expansion plan recommended delaying the decommissioning after 2020 in order to mitigate the growing shortage of power supply. Combined capacities of these steam turbine power plants amount to 495 MW. An equivalent installed capacity of CSP plants could be potentially integrated into these systems. Similarly, CSP plants could be integrated in existing gas turbines if a second stage turbine will be incorporated into these systems. The CSP potential for gas turbines would be equivalent to second stage turbine capacity which is 1329 MW.

In any part of the country identified by the DLR study, a CSP power plant can be technically constructed. In the highlands and desert areas, though the water supply issue may be critical but dry cooled parabolic trough technologies are the possibility. Investment costs for dry cooling are 3 % higher than the water cooled systems. Also with dry cooling, there will be an additional 4 percent loss in power due to higher temperature in the condenser, and 4 percent loss for the power needed for fan cooling. But this may be compensated with high solar radiation levels in the highlands thus getting more power from the available solar resource.

In coastal areas, as specified by the DLR study, the possibility of combining with solar desalination exists. A huge potential also exists for this possibility which is estimated to be 186 GW.

3.5.3 Solar Water Heating Potential

3.5.3.1 Domestic solar water heating potential

Significant demand exists for domestic water heating in the highlands of Yemen (altitude of more than 1000 meters above sea level and situated between 14°-17° latitude North and 43.2° - 46.2 longitude) particularly during winter when the weather is cold and dry. Solar water heating offers a good opportunity for the highlands since during this period the solar radiation availability is high (more than 8 hours per day).

The highland governorates include Saadah, Amaran, Sana'a, Al Mahwit, Dhamar, Al-Beida, Taiz, Ibb, Lahj, Al-Dhale'e, Raima, Hadramout (partly), Hajjah (partly). This region represents around 50% of the national grid electricity demand. In estimating the solar water heating potential, only urban households were considered and since there is an existing solar water heater market in the country, the study assumes an initial penetration rate of 10 percent.

Urban households' electricity demand for water heating was disaggregated based on PEC electricity demand categories. The household water heating load assumptions and solar water heater sizes per household category used in the study are summarized in Table 3-11. The consumers' annual costs of electric water heating also represent their willingness to pay for solar water heating services. Category 2 customers have the lowest willingness to pay of US$ 35 per year while Category 4 customers have the highest with around US$ 283 per month.

From the information on the population, the average size of households, and the share of rural and urban households in each governorates, the potential penetration of solar water heaters in the highlands were estimated. In disaggregating the size categories of solar water heaters, the study uses the demand distribution profile of the existing PEC consumer category in the highlands. A total of 299 MW_{th} potential exists for domestic solar water heating in highland governorates which require almost 445,000 m2 of collector area (Table 3-12).

Table 3-11: PEC Consumer Water Heating Load (Highlands)

PEC consumer category	1	2	3	4
Monthly Consumption (kWh) [1]	1-200	201-355	351-700	>700
Number of customers[1]	333,000	71,000	40,000	8,500
Fraction of electricity as water heating load[1]	0	26 –35%	40 – 50 %	50 – 60 %
Annual cost of electric water heating ($)[2]	0	35	111	283
Solar water heater system size (m^2) [2]		2*	4	6
Solar water heater system price(US$) [2]		200*	350	600

Notes: Category 1 consumers have an average electricity consumption of 107 kWh/month, and this household demand level rules out the possibility of having an electric water heater. * There are only 2 solar water heater sizes available in the market: 4 m^2 and 6 m^2 units. Hazza, G. and Al-Ashwal, A. (2006) in their study concluded that is not economical for category 2 consumers to use 4 m^2 units, and estimated that the most appropriate and financially viable system size for this consumer category is 2 m^2 with unit price of US$ 200.

Source: [1] Hazza, G., Al-Ashwal, A. and Al-Ashwal, N. (2006); [2] Hazza, G. and Al-Ashwal, A. (2006)

Table 3-12: Solar Water Heating Potential in Highland Governorates

Governorate	Number of systems	Category 2 2m²	Category 3 4m²	Category 4 6m²	Total collector area (m²)	**Potential MW_{th}**
Sadah	2567	1489	840	239	7768	**5.213**
Amran	3361	1949	1099	312	10170	**6.824**
Sanaa	560	325	183	52	1695	**1.138**
Sanaa city	64671	37504	21156	6010	195696	**13.131**
Dhamar	5781	3352	1891	537	17492	**11.737**
Al Beida	3043	1764	995	283	9207	**6.178**
Taiz	21878	12688	7157	2033	66204	**44.423**
Ibb	11391	6606	3727	1059	34471	**23.130**
Lahj	1389	805	454	129	4202	**2.820**
Dhalee	1627	944	532	151	4923	**3.304**
Raima	12222	7088	3998	1136	36983	**24.816**
Al Mahweet	1271	737	416	118	3845	**2.580**
Hardramout (partly)	12733	7384	4165	1183	38530	**25.854**
Hajjah (partly)	4525	2624	1480	421	13692	**9.188**
Total	**147018**	**85259**	**48095**	**13663**	**444879**	**298.514**

Notes: 1) partly means 50% of households in each Governorate were considered; 2) the number of systems is estimated from the number of households, and initial 10% penetration level were considered; 3) consumer category distribution is based on the existing PEC consumer distribution in highland governorates; 4) thermal to rated power conversion factor used is based on IEA: 1 m^2 = 0.671 kW_{th}

3.5.3.2 Non-domestic solar water heating potential

Hotels and hospitals offer further centralised hot water demand centres to the solar thermal market. Although it is known that there is upwards of 500 hotels in Yemen, little is known about the individual hot water systems installed. It is common that bathrooms are individually fitted with an electric hot water tanks. In some of the larger more modern hotels, there are centralised hot water systems which lend themselves to retro-fitting with solar thermal support for hot water preparation. However, since systems are generally sized to meet maximum demand, an assessment based on hotel capacity is considered. In 2004, traditional as well as 1, 2, 3, 4 and 5 star hotels have a collective bed capacity of 30,142 and the study assumes all beds require hot water for one person.

Accounting for water shortage issues in Yemen, a conservative estimate of the hot water demand for each hotel guest of 60 litres person (the European average is 100 litres), will yield a further potential available for solar exploitation. Making the following assumptions, the required solar collector area for the preparation of hot water is calculated based on the formula shown in Table 3-13. The technical potential for hotels is estimated to be 27.5 MW_{th} which requires around 20,500 of 2m x 1m solar collectors (Table 3-14).

Similarly, for hospitals, hot water demand is assessed as a function of the number of beds. For Europe, 60 litres per bed is assumed. In Yemen, the health service supports approximately 12,500 hospital beds. Taking a more conservative estimate for water demand, say 35 litres per bed, and with the same assumptions as for the hotel sector, a further technical potential of 6.7 MW_{th} for solar thermal collector area of 9,924m^2 exists (Table 3-15).

Table 3-13: Solar Collector Area Calculation

Solar collector area = E/Q
where
• E = hot water demand per day = $\Delta T\, C_p\, l$;
• Q = energy gained by solar water heater technology = ηR
ΔT = average increase in water temperature = 35 ^{o}C
C_p = specific heat capacity of water = 4.2 kJ/l/^{o}C
l = water consumption = 60 L
η = Solar thermal system efficiency = 0.3
R = average daily insolation = 6 kWh/ m^2

Table 3-14: Solar Water Heating Potential for Hotels

Hot water demand	8,820 kJ
Energy gained by solar water heating technology	6,480 kJ/ m^2
Number of beds	30,142 units
Collector area to meet hot water demand per person	1.36 m^2
Total collector area	40,993 m^2
Equivalent installed power	**27.5 MW_{th}**
Equivalent number of 2m x 1m solar collector units	20,497 units

Table 3-15: Solar Water Heating Potential for Hospitals

Hot water demand	5,145 kJ
Energy gained by solar water heating technology	6,480 kJ/ m^2
Number of beds	12,500 units
Collector area to meet hot water demand per person	0.794 m^2
Total collector area	9,925 m^2
Equivalent installed power	**6.7 MW_{th}**
Equivalent number of 2m x 1m solar collector units	4,962 units

3.5.4 Technical Potential for Identified Applications

As presented earlier, the theoretical potential for solar energy in Yemen is enormous. Similarly, the gross technical potential is also in the order of gigawatts as indicated by the estimated CSP technical potential alone. In this study, the technical potential for identified energy services using solar energy technologies such as solar home systems, solar PV as fuel savers, concentrating solar power and solar water heating is being estimated. One finds that the solar energy potential for these applications could reach as high as 2200 MW (Table 3-16).

Table 3-16: Technical Potential for Identified Solar Energy Applications

	Technical Potential (MW)
Solar Home Systems	**43.4**
Urban	3.2
Rural	40.2
Concentrating Solar Power	**1824**
CSP integrated with steam power plants	495
CSP combined with gas turbines	1329
Solar Water Heating	**332.7**
Residential	298.5
Hotels	27.5
Hospitals	6.7
TOTAL For identified applications	**2200.2**

4 Geothermal Energy Resource Assessment

4.1 Geothermal Energy Resource Assessment Methodology

The study reviewed and evaluated the past geothermal resource assessment studies in Yemen, and carried out resource assessment study for areas not covered by these studies. The past studies focused mainly resource assessment potential in the near volcanic district of Dhamar-Radaa area where the probability of finding a geothermal site suitable for power generation is high. For other parts of the country, there was no specific attempt to investigate and evaluate the geothermal resource potential for power generation. This study estimated the resource potential of other regions of the country. A volume model which estimates the 'heat-in-place' of a specific rock layer was developed to assess the resource potential of Yemen's tectonic plate areas.

4.2 Geothermal Energy Resources

Yemen is situated near three tectonic boundaries which are among the most active areas of the world. These are the Gulf of Aden, the Red Sea and the Eastern African Rift System. Figure 4-1 shows the geological activities of the dynamic earth nearby Yemen. The three tectonic plates meet in a triple junction which result in high geothermal gradient, and subsequently geothermal energy potential. In the Red Sea region, geothermal gradients range from 40°C/km to 77°C/km. The worldwide geothermal gradient average is only at around 30 °C/km.

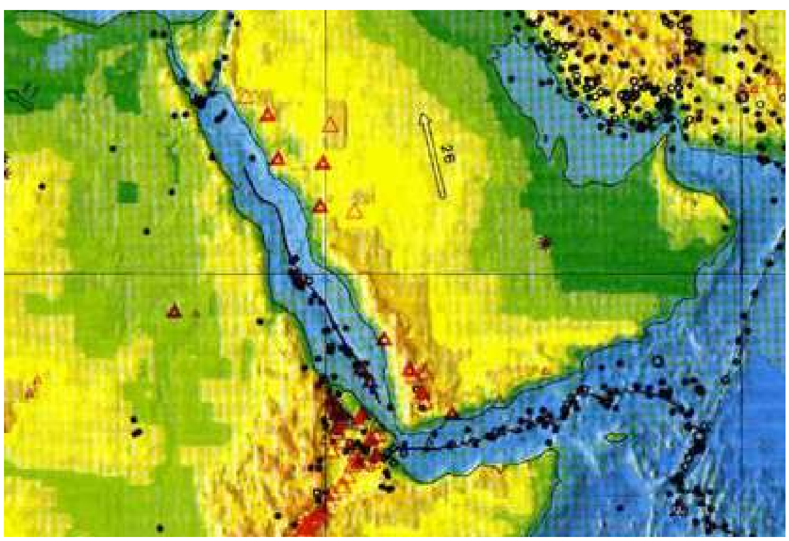


Figure 4-1: Volcanic and Earthquake Activities
(red triangle represents volcanic activities, black dot denotes earthquake activities)
Source: World Map of Volcanoes, Earthquakes, Impact Craters, and Plate Tectonics, 1994.

Several geothermal springs and gas vents are spread in Continental Yemen. These springs can be grouped into the following:

- Springs emergences at high elevation (1000 – 2000 meters above sea level) inside the Yemen Trap Plateau, in a triangle delimited by Sana'a to the North, Damt to the Southeast and Ta'iz to the South.
- Spring emerging at elevations between 300 – 1300 meters located in the Lahj, Abyan and Shabwah region
- Spring emergences at elevations ranging 200-400 meters along the Great West Escarpment bordering the Western edge of the Yemen Trap Plateau from North of Hajjah to Southwest of Ta'iz.
- Thermal discharges of the Hadramaut region with spring locations near the coast at elevation below 1000 meters above sea level.

A geothermometric analysis undertaken by M.A. Mattash et al (2005) has indicated the following geothermal resources of Yemen:

- Low enthalphy resources (70-80°C) with good potential exist in the sedimentary cover areas,
- Low-medium enthalpy resources (80-120°C) under limited pressure exist in the methamorphic basement region,
- Medium enthalpy resources (100-140°C) are associated with the Western Yemen volcanic province,
- High enthalpy potential in some regions such as the Dhamar area (presence of fumaroles), the high heat flow in the Red sea area (also supported by drilling data shown in Table 4-1), and sedimentary cover springs (indications of deep temperature exceeding 150°C).

Table 4-1: Temperature Data from Oil Drilling at the Red Sea

Well Site	Depth	Temperature	Calculated Gradient	Projected Depth: 200 °C Isotherm
Salif 1	1,378 m	--	59 °C/km	2,950 m
Salif 2	2,223 m	--	59 °C/km	2,950 m
Hudaydah 1	1,729 m	96 °C	53 °C/km	3,280 m
Hudaydah 2	2,733 m	129 °C	51 °C/km	3,410 m
Zaydiyah 1	3,018 m	152 °C	50 °C/km	3,480 m
Kathib 1/1a	2,459 m	167 °C	70 °C/km	2,490 m
Al Auch 1	2,812 m	170 °C	54 °C/km	3,220 m
Abbas 1	3,141 m	174 °C	50 °C/km	3,480 m

Source: Geothermal Assessment Study, GeothermEx, Inc., 1984

The potential geothermal fields in Yemen are shown in Figure 4-2. Among these, the fields that show high geothermal potential suitable for power generation exploitation are those situated in the areas of Al Lisi, Al Makhaya and Damt.

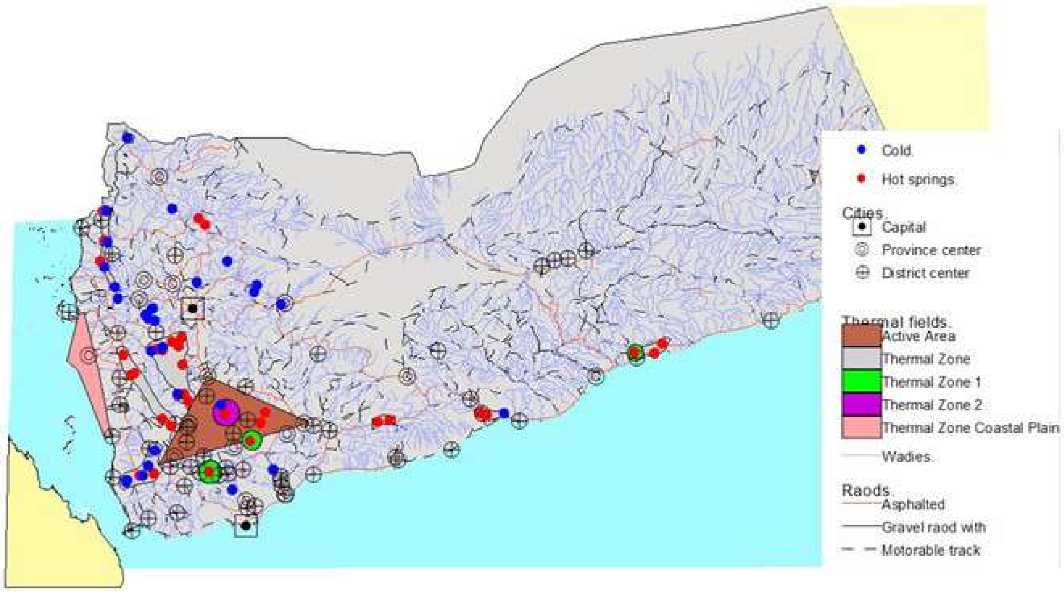


Figure 4-2: Prospective Geothermal Fields in Yemen

Source: Geochemistry, Gas and Isotopic Composition and Rare Earth Elements in Continental Geothermal Systems of Yemen, Mattash M. A., University of Idaho, USA and Geological Survey and Mineral Resources Board, Ministry of Oil and Minerals; Yemen, 2004

4.3 Geothermal Resource Potential: Dhamar Region

Geothermal springs in the Yemen Trap Plateau offer the highest probability of finding a high temperature hot water reservoir. Among the geothermal fields in the Yemen Trap Plateau, Dhamar has the highest potential due to the presence of steam vents (fumaroles) and hot ground water in a young volcanic field. Also, Dhamar is accessible and proximate to a national transmission network. Geologic, geochemical and electrical resistivity investigations were undertaken in the geothermal prospect area by ELC-Electroconsult. Reinterpretations of ELC's results and estimates of the geothermal resources were carried out by GeothermEx, Inc.

4.3.1 Geochemical survey

The geochemical survey can determine the presence of geothermal reservoir through the analysis of major chemical constituents. The temperature of the reservoir can also be estimated through chemical analysis. The geochemical survey results are summarized as follows: i) the Cretaceous sandstones of the Tawilah Group are permeable and this extends, to some extent, to the overlying Yemen volcanics; ii) a geochemical anomaly was found east and southeast of Al Asi volcano to just south of the Isbil volcano. This anomaly indicates permeable zones and high temperatures; and

iii) the initial interpretation of geochemical thermometry of the sampled waters shows maximum temperatures in excess of 200°C. GeothermEx, Inc. re-analysis of the results, however, shows a lower temperature range from 16°C to 134°C. These are, however, considered as minimum temperatures.

4.3.2 Electrical resistivity survey

A subsurface electrical resistivity survey can map out the area of a geothermal reservoir. Low resistivity, in geothermal prospects, indicates accumulation of hot saline fluids in a geothermal reservoir. Low electrical resistivity, combined with other favourable features such as high temperature gradients, a zone of hot springs, steam vents or recent volcanic extrusions, indicates that the electrical resistivity anomaly is caused by a geothermal reservoir.

The results show that the area with low resistivity (15 to 20 ohm-meters) parallels the zone of intersection of the Al Jurashah fault zone. Geothermix Inc estimates that the area with anomalous electrical resistivity starts from Al Asi volcano (southwest end of the the area) and extends 10 kilometers northwest. The width of the anomaly expands 2.5 kilometers.

4.3.3 Radon gas survey

A radon gas survey can also determine permeable geothermal system. The presence of radon gas in the surface could indicate an accelerated transport of the gas due to the presence of geothermal system or a presence of radon gas source rock at very shallow levels and has nothing to do with a geothermal system. Radon gas normally diffuses rapidly upwards through rock formation. Because of its short half-life, radon gas released from depths more than few hundred meters will never reach a surface unless it travels along open fault planes, geothermal convection cells, or within permeable media.

The survey shows that i) areas identified with geophysical and geochemical anomaly have higher rates of radon gas leakage, ii) anomalous trends of radon gas release are parallel but not coincident to known faults suggesting that there are several actives faults in the area, iii) absence of radon gas in other areas.

4.3.4 Technical potential

Dhamar's unit area productivity was estimated not through the survey results but through analogy with other fields in volcanic settings with more or less similar characteristics. The prospect area is estimated to yield an average unit area productivity of 20 MW/km^2. Taking only 25 to 50 percent of the area with electrical resistivity anomaly to be productive, the total geothermal electric power potential of Dhamar region could range from 125 MW to 250 MW.

4.4 Geothermal Resource Potential: Other Regions

With regard to the tectonic plate boundaries near the Yemen coast, geothermal potential could also be high. The study estimated the potential for geothermal power generation in these regions.

4.4.1 Database

The current situation related to the required data necessary to undertake a geothermal resource assessment is insufficient. Various assumptions were made using international figures in order to complete the assessment study.

Eight geological maps exist for the former North Yemen (Figure 4-3). These maps are all created by the Ministry of Oil and Mineral Resources, Sana'a, Yemen and the Federal Institute of Geosciences and Natural Resources, Hannover, Germany in 1991. The sheets of Aden and Tai'zz were updated in 1996.

These maps show the surface geological situation on the country. This information however is not useful for geothermal evaluation purposes because the data from the surface might not be related to the geological data below the surface. Six of the maps (map 1 to 6), however, include a typical stratigraphy of the earth under the surface. The stratigraphy contains information on the different formations and their thickness. These stratigraphies are the basis of this geothermal resource assessment study. They are used to analyse the heat below the Earth's surface which can be used for generating electrical power.

Figure 4-4 shows which part of Yemen is covered by those 6 geological maps. Assuming that the Yemen has an area of 528,000 km², these maps cover 27% of this area (142,072 km²).

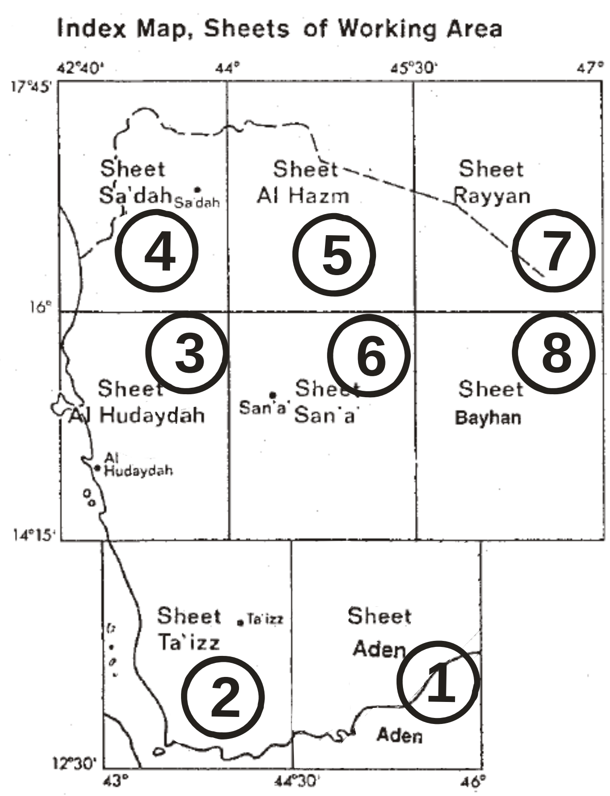


Figure 4-3: Geological maps of the study area

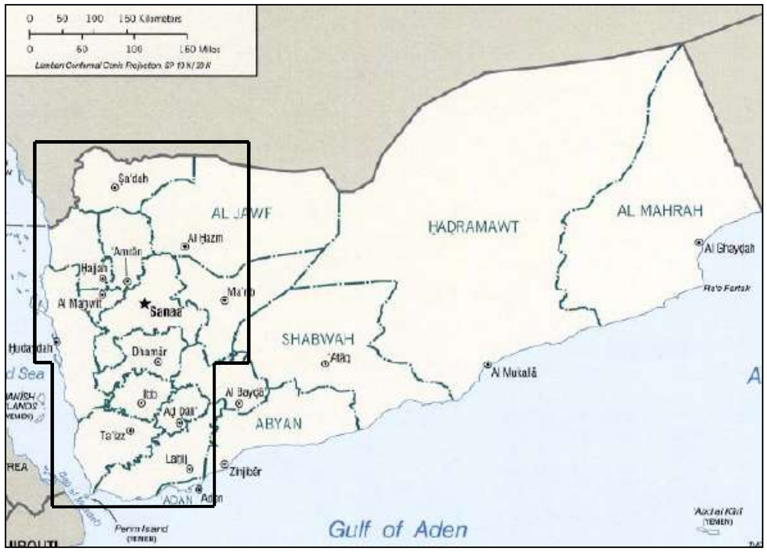


Figure 4-4: The geological maps (area bordered with black lines) cover 27% of Yemen

4.4.2 Stratigraphical information

A stratigraphy describes the Earth's layers beneath the surface. The given stratigraphies picture the layers into depth from 1,290 m (map 5) until 4,515 m (map 4). At the lower part of these layers, there is always a basement structure expected, built of Gneiss, schist, granite etc.

The stratigraphy of map 6 is given in Figure 4-5. It can be seen that this is composed of different layers of stones and rocks such as volcanics, sediments and basement rocks. Looking into one layer in detail such as the volcanics, more differentiations are made. These differentiations contain the specific name (and thus the specific physical properties) of these layers. Sometimes they are acidic, sometimes they are basic. But the authors of the maps numbered all together with one amount for the thickness. Beginning from a depth of 2,000 meters beneath the surface the layers with sedimentary stones are mentioned. The thickness of these layers sometimes is also counted as one amount for several layers. For example, there are three different facies of Amran Limestones given in Figure 4-5 but their thickness is marked all together with 2,000 m.

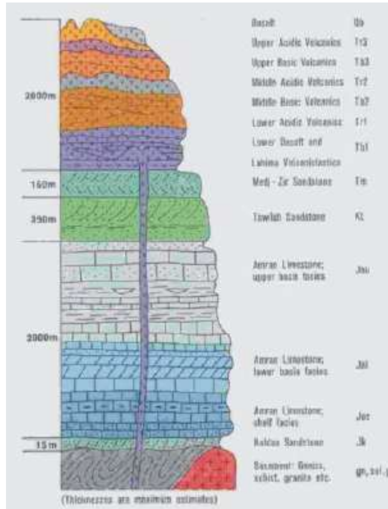


Figure 4-5: Stratigraphy taken from sheet 6, Sana’a

4.4.3 Calculation model and data needed

To describe the geothermal resource the volume method is used in the study. In this method, the geological layers beneath the surface are regarded.

The so called “heat in place” can be calculated using the formula:

$$Q = \rho * V * c_p * (T_i - T_B)$$

Where Q is the heat in place

ρ is the density

V is the volume (as the product of the area and the thickness)

c_p is the heating capacity

T_i is the initial temperature

T_B is the refererence temperature

To apply this formula to the geological situation, information on the physical properties of the layers is needed. It is necessary to determine the density, heating capacity and initial temperature of the geological formation.

4.4.4 Density and heating capacity

These physical properties from the formations are taken from the literature. Unfortunately there are no specific data available for Yemen. Thus, the data are taken as averages from the available references. This is summarized in Table 4-2.

For some layers, it was necessary to calculate the averages. They were counted as an average of the above given data. These cases are shown in Table 4-3. Also, the estimated averages are given in the said table.

Table 4-2: Heating capacity and density for different formations

	Heating Capacity [1]	Density [2]
Upper Acidic Volcanics	900 J/kg	2.620 kg/m³
Upper Basic Volcanics	1.231 J/kg	2.770 kg/m³
Middle Acidic Volcanics	900 J/kg	2.620 kg/m³
Middle Basic Volcanics	1.231 J/kg	2.770 kg/m³
Lower Acidic Volcanics	900 J/kg	2.620 kg/m³
Lower Basalt	1.231 J/kg	2.770 kg/m³
Medj – Zir Sandstone	970 J/kg	2.620 kg/m³
Tawilah Sandstone	970 J/kg	2.620 kg/m³
Amran Limestone (upper basin facies)	890 J/kg	2.675 kg/m³
Amran Limestone (lower basin facies)	890 J/kg	2.675 kg/m³
Amran Limestone (shelf facies)	890 J/kg	2.675 kg/m³
Kohlan Sandstone	970 J/kg	2.620 kg/m³
Akbra Shales	890 J/kg	2.640 kg/m³
Upper Wajid Sandstone	970 J/kg	2.620 kg/m³
Lower Wajid Sandstone	970 J/kg	2.620 kg/m³
Basement: Gneis, Schist, Granite	950 J/kg	2.630 kg/m³

Sources: [1] Petrophysik, physikalische Eigenschaften von Gesteinen und Mineralien, Jürgen Schön, Enke Verlag, 1983; [2], Ländolt-Börnstein, Physikalische Eigenschaften der Gesteine, Hrsg: G. Angenheister, Neue Serie, Gruppe V: Geophysik und Weltraum, Band 1, 1982

Table 4-3: Averages for the cases with more then one formation

	Heating Capacity	Density
Upper, Middle, Lower Acidic and Upper, Middle Basics and Lower Basalt Volcanics	1.066 J/kg	2.695 kg/m³
Lower Acidic and Middle Basics and Lower Basalt Volcanics	1.148 J/kg	2.733 kg/m³
Amran Limestone: Upper Basin, Lower Basin and shelf facies	890 J/kg	2.675 kg/m³

4.4.5 Initial Temperature

The initial temperature for different layers in different areas is not available. The study used a constant geothermal gradient model to determine the initial temperature. The yearly average temperature of the Earth next to the surface is around 20 °C. For areas 3 and 6, it is known from the literature and personal communications with the experts from Ministry of Oil and Minerals that the geothermal gradient is very high in some regions. It could reach as high as 90 K/km, but there are only few regions in these areas with this gradient level. The study uses a lower gradient of 70 K/km as an average for area 3 and 6. Non-active volcanoes also exist in these areas. These geological structures are often combined with high convectional heat transfers. Thus, the lines with equal temperature don't follow the horizontal direction. They are sometimes in vertical direction. The result is, that there is high temperature close to the surface but nearly no increase of this temperature with the depth. Figure 4-6 demonstrates this situation.

Following this trend of the temperature in the depth, the study set a limit of the temperature to maximum 280 °C (Figure 4-6). For all other areas, the geothermal gradient is assumed with 50 K/km. Figure 4-7 and Figure 4-8 show the temperature in the depth until 5,000 m for those gradients.

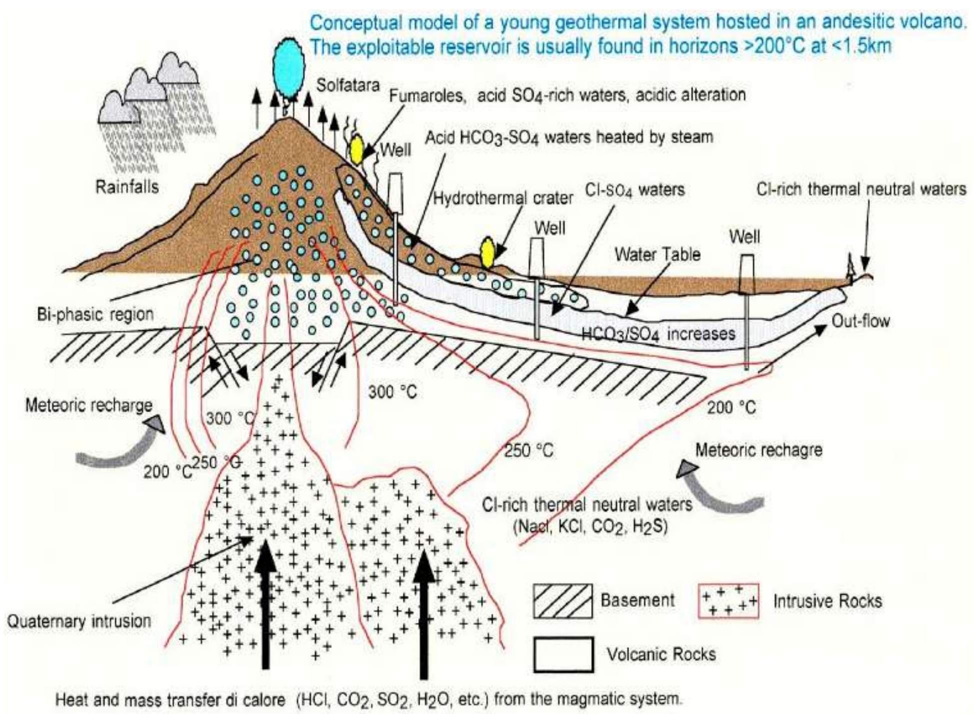


Figure 4-6: Geological situation at volcanoes areas

Source: Geochemistry, Gas and Isotopic Composition and Rare Earth Elements in Continental Geothermal Systems of Yemen, Mattash M. A., University of Idaho, USA and Geological Survey and Mineral Resources Board, Ministry of Oil and Minerals; Yemen, 2004

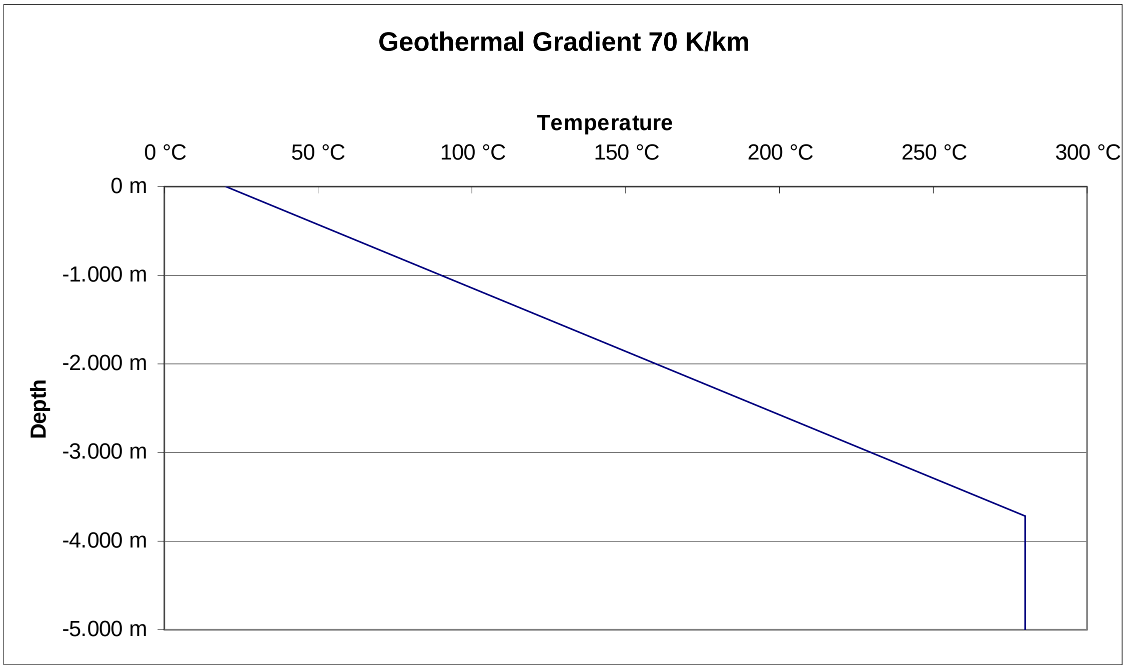


Figure 4-7: Temperature in depth, geothermal gradient of 70 K/km, maximum 280 °C

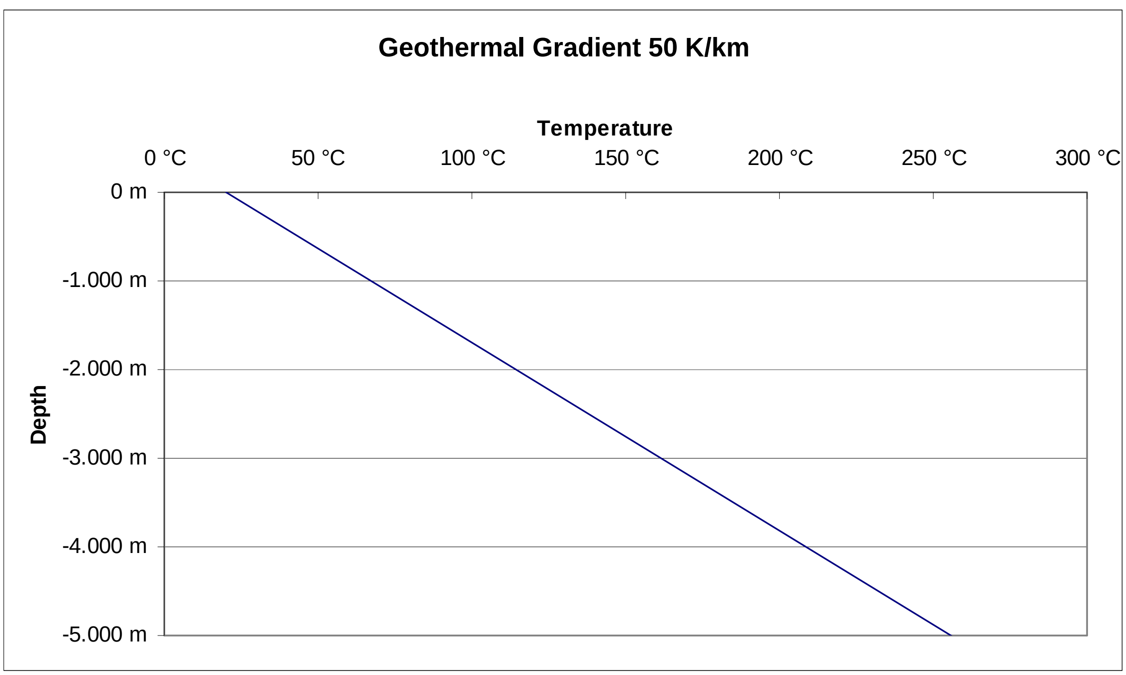


Figure 4-8: Temperature in depth, geothermal gradient of 50 K/km

With the knowledge of the average depth of each layer from the stratigraphical information, it is possible to calculate the initial temperature. For proper assessment it is also necessary to know the amount of water in the formations (for example in percent of the volume) and the pressure. This is because the heat included in the water can be calculated following the same 'heat in place' formula. The pressure together with the initial temperature fixes the density and heating capacity of the water.

4.4.6 Reference temperature

The selected reference temperature affects significantly on the study results. The selected temperature in the study represents the lower temperature range to calculate the heat in place. In estimating the "overall" theoretical potential, it might be correct to choose the average surface temperature. This is mostly done in the literature.

The objective of this assessment is to line out the heat in place which can theoretically be converted into electrical energy. Running processes to convert heat into electrical energy means that the temperature of the heating medium (i.e. the fluid taken from the earth) must be around 80°C at the end of the process. Thus, the study assumed this temperature boundary condition. The study also considered an average temperature in the analyzed layer of more than 120 °C. This is the necessary temperature to run a process to generate electrical power. There is the chance to generate power from water at temperature lower than 100 °C. But doing this leads to very low efficiencies of the converting technology.

4.4.7 Correcting factors

The calculation of the heat in place with the described inputs leads to the *Theoretical Potential* for the power generation. This amount must be corrected with at least two factors to generate the *Technical Potential.*

4.4.7.1 Recovery factor

The first factor corrects the amount with regard to the incomplete extraction of the heat. This is also called as *recovery factor*. The incomplete recovery might be caused by the number of plants which are settled to use the regarded layer. It might also be caused by the (technical or economical) useful "density" of plants. All counted plants must run without affecting each other. Thus their distance from each other must be larger than the by extracting heat influenced area.

Another (geometrical) influence is given by the non-homogeneous structure of the layers. There is different permeability at several points of the thickness of the layers. Thus there is a heterogeneous distribution of the cooling.

Also the locations where the plants should be erected have influence on this factor. This is because some locations on the surface may not be useful for a plant while there is no grid to deliver the produced electrical power to and/or no possibility for a proper cooling system, or existing administrational laws deny the erection. This factor also can be used to calculate the positive influence of strong thermal convections in the earth as sometimes given in volcanic areas (Figure 4-6).

In comparison with aquifers and granites, there are different technologies to recover the heat. In case of aquifers, the natural water with its initial heat is used and lifted aboveground. In case of granites large heat exchangers in the ground are created mostly with hydraulic fracturing. Water comes from aboveground and is heated in that heat exchangers before lifted again. In this case the recovery factor is lower than for the aquifers because the process of heat transfer to the water is a complex system with several non-homogeneities.

Concerning these information and knowing that Tawilah Sandstone as an aquifer with very good conditions, three different factors were used in the study for different geological layers. This is given in Table 4-4.

Table 4-4: Recovery factors for different layers

Layer	Recovery factor
Tawilah Sandstone	5 %
Basement: Gneiss, Schist, Granite	1,5 %
Other Layers	3 %

4.4.7.2 Efficiency factor

The second factor concerns the efficiency of the conversion from heat to power. This factor is strictly connected to the initial temperature. With rising temperature the “efficiency factor” rises.

There is also a big influence given by the enthalpy and by the mixture of liquid and steam of the extracted fluid. Depending on the following processes (i.e. flash process with only steam turbine) there may be an amount of “unused” heat in liquid water reinjected into the earth. Other plant constellation may combine this process with an ORC- Process which takes additional heat from the injected water.

The way of cooling the condenser is very important. Cooling with water is very efficient but not always possible. Dry cooling by using ambient air leads to higher condensing temperatures and to additional power consumption for the ventilation.

To realise the geothermal resource assessment, the counted efficiencies of the processes are displayed in Figure 4-9. From the said figure, the study used the efficiency factors for results with temperatures below 200 °C. For temperatures higher than 200 °C, the study used the ‘adjusted’ Carnot efficiency factor. The adjustment is done due to the fact that the Carnot factor is a theoretical result which can not be reached in real processes.

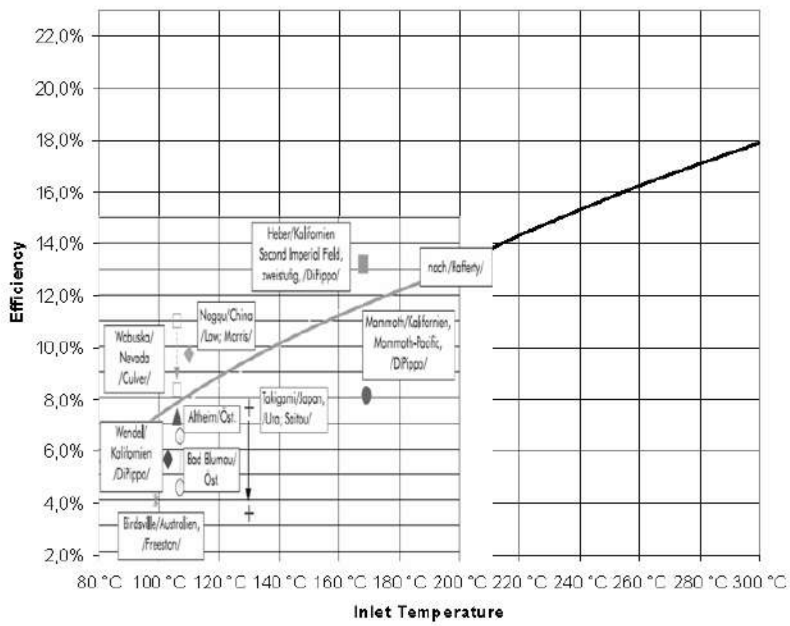


Figure 4-9: Calculated efficiency of the conversion processes for different inlet temperatures

Source: Möglichkeiten geothermischer Stromerzeugung in Deutschland, Sachstandsbericht TAB, Herbert Paschen, Dagmar Oertel und Reinhard Grünwald, 2003

4.4.8 Results

With the above information, assumptions, and theoretical basis, the amount of heat in place for different study areas was estimated. The results are summarized in Table 4-5.

Table 4-5: Results of the geothermal resource assessment for the six considered areas

Number of Sheet (Figure 4-3)	Area	Heat in Place (Theoretical Potential)	Recoverable Heat (Technical Potential for Heat)	Recoverable Electrical Energy (Technical Potential for Energy)
Sheet 1	21.936 km²	5,5E+15 kWh	8,2E+13 kWh	1,0E+13 kWh
Sheet 2	23.579 km²	5,3E+15 kWh	1,0E+14 kWh	1,3E+13 kWh
Sheet 3	24.061 km²	8,6E+15 kWh	1,8E+14 kWh	2,6E+13 kWh
Sheet 4	16.063 km²	4,0E+15 kWh	8,5E+13 kWh	1,0E+13 kWh
Sheet 5	25.140 km²	6,3E+15 kWh	9,4E+13 kWh	1,1E+13 kWh
Sheet 6	31.292 km²	1,1E+16 kWh	3,3E+14 kWh	5,1E+13 kWh
Total	**142.072 km²**	**4,1E+16 kWh**	**8,7E+14 kWh**	**1,2E+14 kWh**

The third column shows the heat in place. This is the theoretical heat potential in all layers of the six areas. It does not include recovery or efficiency factors. This represents the theoretical potential.

The fourth column gives the corrected values using the different recovery factors. This is the technical potential for heat. This is the heat which can be conducted to the surface of the earth. The different recovery factors for the different layers are calculated before summing up the results.

The fifth column corrects the recoverable heat with efficiency factors. Along that way the recoverable heat is converted to electrical power. These efficiency factors are also taken into account before summing up. Thus the efficiency is calculated for different inlet temperatures. This column gives the technical potential for electrical energy.

The study results show an enormous geothermal resource potential. Even after accounting the two correction factors, the recoverable power from plants is very high. Assuming that all this power will be recovered the current amount of gross production can be delivered for a period of about 30,000 years.

The basis for this table is to use all thermal energy which can be recovered until a depth of 5,000 m. This basis does not reflect currently given restrictions. The use of some layers may be difficult because of a low flow rate of the natural water. This may happen in some layer like limestone or shale, sometimes also in some of the sandstones. Consequently it is not possible to produce enough heat from the earth and to drive a plant with sufficient economical results.

Another point is that the use of the basement layers is bounded to the implementation of Hot Dry Rock (HDR) technology. This is not a “state of the art” technology at present. It is under development and it will be a good chance for using geothermal energy in the future. Currently, this technology and the associated layers should be considered in an assessment, but not in the first line.

About the geophysical properties (including permeability and transmissibility) currently no detailed knowledge is available. This can be acquired by test drillings.

Concerning the Tawilah Sandstone there seem to be good conditions for the geothermal use of the included water. The natural water comes to the surface (by own in artesian systems and by pumps in other systems) and can be spent in Flash Processes and/or Binary Processes, depending on the temperature and chemical processes. These technologies are proven technologies and being used.

Paying attention to those facts, it could be sensible to present the results in another way. Table 4-6 shows the energy yields from different classes of layers in the six areas.

The first column displays the class of layer called volcanics. This includes all layers which were formed by volcanic activities (the Upper, Middle and Lower Volcanics, the Basalts and the Lahima Volcaniclastics). This is not the area with high convection from the nearby caldera. In these layers in each area there is no potential for geothermal power generation. This is because these layers are situated in depth until maximum 2.500 m. The calculated average temperature is only 90 °C and therefore to low for the generation of power.

Table 4-6: Results for different classes of layers of the six areas

Areas	unit	Volcanics	Tawilah Sandstone	Other Sandstones	Limestones and Shales	Basement
Sheet 1	kWh	0	0	0	0	1,0E+13
	kWh/m²	0	0	0	0	457
Sheet 2	kWh	0	2,6E+12	5,6E+11	1,0E+12	9,3E+12
	kWh/m²	0	109	24	43	396
Sheet 3	kWh	0	3,3E+12	1,7E+12	6,8E+12	1,4E+13
	kWh/m²	0	135	71	284	594
Sheet 4	kWh	0	0	1,9E+12	3,4E+12	5,1E+12
	kWh/m²	0	0	118	209	316
Sheet 5	kWh	0	0	0	0	1,1E+13
	kWh/m²	0	0	0	0	421
Sheet 6	kWh	0	5,6E+12	1,4E+12	3,9E+13	5,2E+12
	kWh/m²	0	178	44	1.244	165
Total	**kWh**	**0**	**1,1E+13**	**5,5E+12**	**5,0E+13**	**5,4E+13**
	kWh/m²	**0**	**423**	**257**	**1.780**	**2.347**
	MW [1]		**28544**	**13836**	**125324**	**136098**

[1] capacity is estimated from electrical energy potential with the following assumptions: lifetime is considered 50 years, and operation hours per year is 8000.

Tawilah Sandstone is displayed in the fourth column. Tawilah Sandstone is separated from Other Sandstones because of the expected good conditions from this layer. In three of six areas geothermal potential is identified. This layer could give a good chance for geothermal use and the recoverable energy is estimated to 1,1 $*10^{13}$ kWh. This is 3,000 times more than the currently given gross production of Yemen. The calculated average temperature is in-between 160 °C and 183 °C. The expected electrical capacity is around 3 MW per well (Table 4-7). This row shows the “most secure” potential for geothermal energy use.

Table 4-7: Electric power estimation assumptions for one well

estimated flow from the well:	250 m³/h ≈70 kg/s
average inlet temperature	170 °C
injection temperature	80 °C
efficiency of power process:	11.7 %

Other Sandstones and also Limestone and Shale may also have good conditions but the knowledge about the transmissibility is low. Consequently, it is necessary to increase the knowledge by observation drillings to sign this potential as “secure”.

For the basement currently no secure potential is lined out because of the necessity to follow up with HDR technologies.

In total, there is an enormous geothermal potential for generating electrical power, even when only “currently secure solutions” are considered.

And this potential rises when the special situation of the volcanic districts (for example Dhamar area) is considered. In the Geothermal Assessment Study of GeothermEx (1984) estimations for the potential of the Dhamar area are documented. Only the nearer surrounding of the Quaternary volcanoes was considered. An attractive prospect has been identified and it was recommended to explore the subsurface in detail. It was included in the report that a developable geothermal field with 100 – 200 MW for 30 years will be found with a probability of 0.6. This leads to another 2.3 * 10^{10} kWh of geothermal potential.

Assuming that other areas are nearly similar there will be a considerable additional potential.

4.4.9 Proposal for further development

The Ministn

5 Small Hydropower Resource Assessment

5.1 Resource Assessment Methodology

The small and micro hydro resource assessment aims at identifying potential sites for small-scale hydropower Yemen using the existing dams and water supply systems. The choice of site is based on a close interaction between the various conditions like the pattern of the river, integrity of the site works, environmental integration and conditions defining the costs and benefits.

Factors considered in estimating the hydro potential include the following: i) topography, ii) head (elevation difference), iii) land use pattern in the catchment, iv) hydrological data (flow and discharge), v) available infrastructure such as irrigation canals or pipes and access roads, vi) distance to the closest over head line, electricity grid and/or consumers (villages, small industries, others), vii) water use priorities, possible social conflicts, and viii) annual average rainfall not less than 400 mm/year.

Data necessary for the analysis were collected such as topographical maps for the study areas (wadi and streams), elevation, land use, hydrological data (rainfall, flow and discharge). With these, existing dams in Sana'a City, Sana'a and Al Mahwit Governorates were investigated for possible development of hydropower stations. Similarly, the potential for hydropower in major wadis of the country was also assessed. Sixteen sites were visited by consultant's hydropower expert to verify the results of the resource evaluation study.

5.2 Overview of Climate and Water Resources in Yemen

5.2.1 Climate

Yemen has a predominantly semi-arid to arid climate, with rainy seasons during spring and summer, and high temperatures prevail throughout the year in low-altitude zones.

Landscapes in Yemen can be grouped into 5 main geographical/climatological regions, and these are summarized below:

- The Coastal Plains: The Plains are located in the west and south-west and are flat to slightly sloping with maximum elevations of only a few hundred meters above sea level. They have warm climates with generally low to very low rainfall (< 50 mm/year).

- The Yemen Mountain Massif: This massif constitutes a high zone of very irregular and dissected topography, with elevations ranging from a few hundred metres to 3760 meters above sea level. Accordingly, the climate varies from warm at lower elevations to cool at the highest altitudes. The western and southern slopes are the steepest but enjoy moderate to rather high rainfall, on average 300-500 mm/year, but in some places even more than 1000 mm/year. The eastern slopes show a comparatively smoother topography and average rainfall decreases rapidly from west to east.

- The Eastern Plateau Region: This region covers the eastern half of the country. Elevations decrease from 1200-1800 meters at the major watershed lines to 900 meters on the northern desert border and to sea level on the coast. The climate in general is hot and dry, with average annual rainfall below 100 mm, except in the higher parts.

- The Desert: Between the Yemen Mountain Massif and the Eastern Plateau lies the Ramlat as Sabatayn, a sand desert. Rainfall and vegetation are nearly absent, except along its margins where rivers bring water from adjacent mountain and upland zones. In the north lies the Rub Al Khali desert, which extends far into Saudi Arabia and is approximately 500 000 km² in area.

- The Islands: The most important of all the islands is Socotra. A rainfall pattern for Socotra Island has not yet been established. Available rainfall data suggest an average rainfall near Hadibo of 100-150 mm per year. Source of moisture are abundant and topography expression is strong; hence, it is probable that rather high rainfall is enjoyed in the higher parts of the island.

5.2.2 Rainfall

The climate of Yemen is strongly influenced by the mountainous nature of the country. Rainfall rises from less than 50 mm along the Red Sea and Gulf of Aden coasts to a maximum of 500-800 mm in the western highlands and decreases steadily to below 50mm inland.

The rainfall depends on two main mechanisms, the Red Sea Convergence and the Monsoonal Inter tropical Convergence Zone. The former influence is most noticeable in the west of the country, this is active from March to May and to some extent in autumn, while the latter reaches the country in July-September, moving north and then south again so that its influence lasts longer in the south. Seaward exposed escarpments such as the western and southern slopes receive more rainfall than the zones facing the interior. The average temperature decreases more or less linearly with the latitude.

Average annual rainfall data higher than 250 mm are only observed in the western and southern parts of the Yemen Mountain Massive, with the maximum near Ibb (1510 mm). Anywhere else the average annual rainfall is low, especially in Al-Mahrah governorate, in the northern part of Hadramawt and in the Ramalat Al-Sabatayen. Figure 5-1 shows the average monthly rainfall pattern in Yemen.

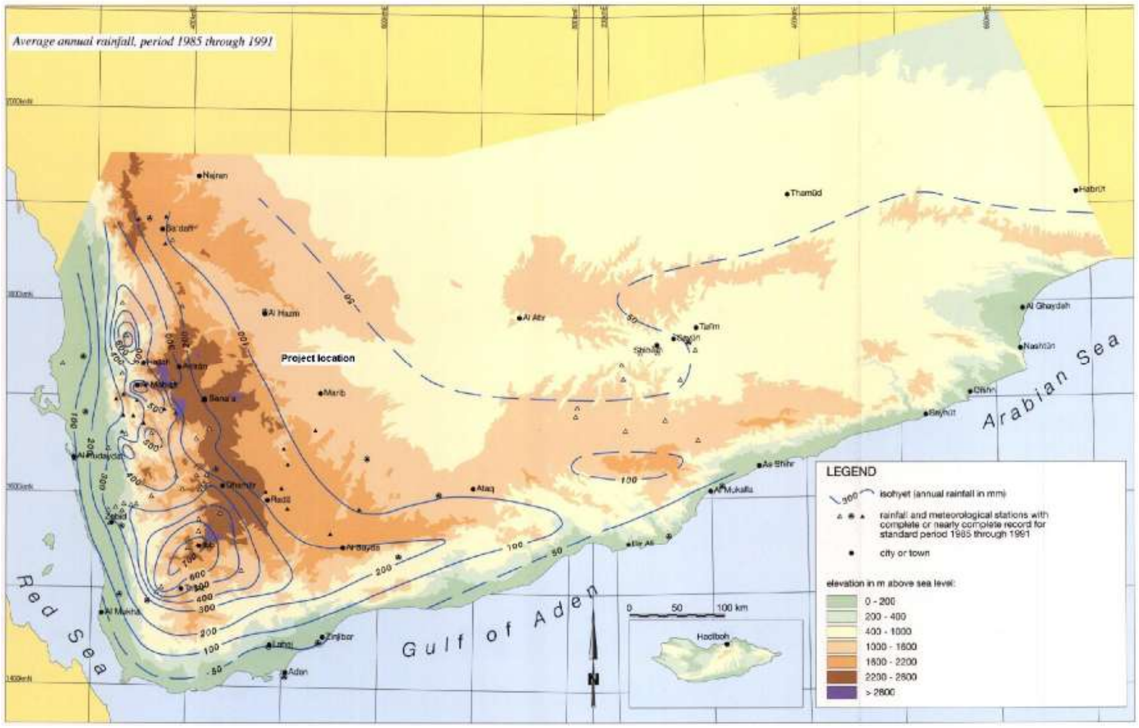


Figure 5-1: Average monthly rainfall patterns for selected rainfall stations

5.2.3 Water Resources

5.2.3.1 Renewable water resources

Yemen can be subdivided into four major drainage basins, regrouping numerous smaller wadis. The floods of the wadis in Yemen are generally characterized by abruptly rising peaks that rapidly recede. In between the irregular floods, wadis are either dry or carry only minor base flows.

Surface water resources have been estimated to be 2.1 billion m³/year but this quantity corresponds to the runoff from major rivers and does not include the runoff produced within the smaller catchments. Water use was estimated at about 2.8 billion m³/year. The country thus overdrew its resources by 0.7 billion m³/year. In general, all surface water sources in Yemen are harnessed and exploited.

Renewable groundwater resources have been estimated at 1525 million m³/year which a large part probably coming from infiltration in the river beds. A major groundwater aquifer was recently discovered in the eastern part of the country with an estimated storage of 10 km³. This aquifer is still under study and it is not known whether the groundwater is rechargeable or whether it is all fossil water.

The surface runoff to the sea measured in some major wadis is estimated at 270 million m³/year, the groundwater outflow to the sea at 280 million m³/year. Recent estimates show that approximately 40 percent of the runoff water comes from the western slopes. The Gulf of Aden, Arabian Sea and Al Rub Alkhali contribute of 30 percent, 25 percent and 5 percent respectively. Annual precipitation in Yemen is estimated to be approximately 65 billion m³.

5.2.3.2 Non-conventional water

Data on non-conventional water is very limited. A brief study carried out by the University of Sana'a shows that the total sewerage flows from the seven major cities in Yemen were estimated to be 16 million m^3/year in 1995. The flow from the seven cities is expected to reach 39 Million m^3/year in 2005.

The sewage treated water quantity is small but it has a strong impact on environment. It is used in agriculture without restrictions. It does not match with the standards and causes pollution to groundwater and deteriorates the soil structure.

Desalination is being discussed as an alternative source of non-conventional water. This option is open for implementation in the coastal plain areas to provide the drinking water for the coastal cities.

5.2.3.3 Rain water harvesting systems

Various methods are used in harvesting rainwater in Yemen. This includes the following: i) rooftop water harvesting systems, ii) terracing, iii) ponds, iv) cistern systems, v) large-scale rainwater harvesting systems, and vi) dams.

- Roof water harvesting is more appropriate in mountainous areas where there are no ground water sources, and where rainwater is the only feasible means of providing a water supply. It has the advantage of being low cost, relatively simple in design (household technology), less laborious and it saves time. It provides adequate water during the rainy season, a period when the rural people are busy with farming activities.
- Terracing is practiced in Yemen highlands to collect rainfall for farming and slow down the runoff process. Rain water collects in the terraces and soaks into the shallow soil. Walls at the edge of the terraces prevent runoff from flowing down to the next terrace except during intense rainfall events.
- Farm ponds are small storage structures used for collecting and storing run-off water. As per the method of construction and their suitability for different topographic conditions farm ponds are classified into 3 categories: i) excavated farm ponds suited for flat topography, ii) embankment ponds for hilly and rugged terrains with frequent wide and deep water courses, and; iii) excavated-cum-embankment type ponds. Selection of the location of the farm pond is dependent on several factors such as potentiality for yielding sizeable quantity of run-off, rainfall, land topography, soil type and structure, permeability/water-holding capacity, land-use pattern etc.
- Cisterns, also known locally as Karif or Majel, are used in the mountainous area of Yemen. It is generally an underground tank, constructed from masonry or concretes and usually covered and used for the collection and storage of surface run-off. Large-scale rainwater harvesting also refers to medium-size catchment runoff farming. This may be a diversion of a natural wadi, or a wadi

flowing from a natural catchment. The collected flow is immediately diverted by a diversion structure to flood irrigate an adjacent agricultural field. The diversion structure may consist of a stone barrier across the wadi or the intermittent stream.

- Small dams existed in Yemen throughout history, as a means of improving water control, breaking spate or enhancing ground water infiltration. Over the last five years the government has embarked on an ambitious "small dam" programme as a response to gravity water storage in the country. The programme at present provides for construction or rehabilitation many hydraulic structures. A typical small dam in mountain regions of Yemen is shown in Figure 5-2.

A total number of these structures are estimated to be about 547, out of which 173 are dams, 145 reservoirs, 195 weirs and 34 unclassified categories. The hydraulic structure which have been completed by May 2000 are 132 (51 dams, 34 reservoirs, 41wiers and 6 unclassified). The total dam capacity is estimated at 0.18 km^3.

In general, the dams are built for irrigation and domestic purposes, but at the same time they contribute to groundwater recharge. There are also many flood control dams, which are not intended to store water, but to divert the spate floods immediately to the adjacent irrigation network (spate irrigation).

Figure 5-2: Typical small dam in the mountain regions in Yemen

5.2.4 Surface water

Rainfall is the main source for surface water in Yemen. Most wadis have temporary base flows, only few have minor base flows that may seasonal or permanent, but only in a limited part of their channels. Wadi beds are dry most of the time, and infrequent runoff peaks quickly occur and disappear. Flood peaks are often quick and infrequent because of sparse vegetation and mostly impermeable nature of the soil in the catchment areas.

Baseflow is nearly constant components of streamflow which may last for long periods without rains. In most cases it is associated mainly with the contribution of groundwater discharging into the rivers. Numerous wadis systems and related catchment areas cover the domain of Yemen. The country is divided into four major drainage basins, regrouping numerous smaller wadis (Figure 5-3 and Table 5-1): Red Sea basin; Gulf of Aden basin; Arabian Sea basin and Rub Al Khali interior basin.

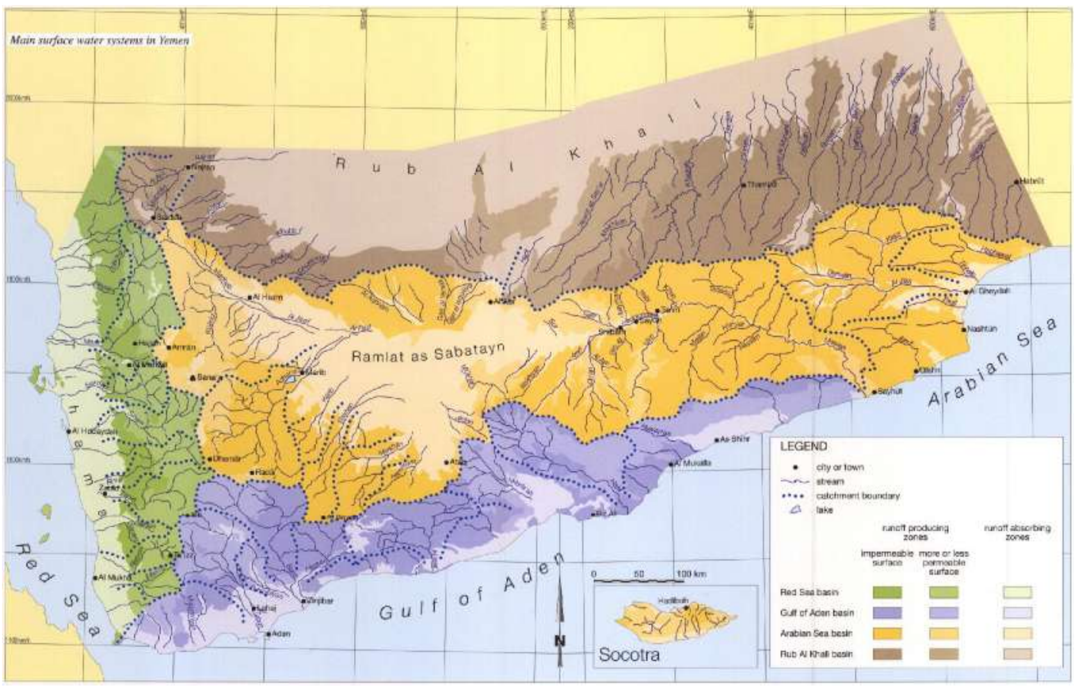


Figure 5-3: Surface water systems in Yemen

Table 5-1: Estimates of mean annual runoff for runoff-producing catchments in Yemen

Surface Basin/Wadi Catchment		Area, km²	Mean Annual Rainfall, mm/year	Mean Annual Runoff, mcm/year
1. Red Sea Basin				
1.1	Wadi Harad	1,700	375	10
1.2	Wadi Mawr	7,910	475	162
1.3	Wadi Surdud	2,700	440	68
1.4	Wadi Siham	4,050	400	89
1.5	Wadi Rima'a	2,750	550	99
1.6	Wadi Zabid	4,450	550	125
1.7	Wadi Rasyan	1,900	465	12
1.8	Wadi Mawza	1,600	325	29
1.9	Minor Wadis	5,850	300	97
Total 1 – Basin		**33,000**	**431**	**691**
2. Gulf of Aden Basin				
2.1	Wadi Tuban	5,060	465	109
2.2	Wadi Suhaibyah	1,400	200	19
2.3	Wadi Bana	6,200	370	169
2.4	Wadi Hassan	3,000	250	41
2.5	Wadi Ahwar	6,420	200	71
2.6	Wadi Mayfa'ah	4,300	100	24
2.7	Wadi Hajar	9,900	100	54
2.8	Minor Wadis West	2,900	100	16
2.9	Minor Wadis East	7,500	75	31
Total 2 – Basin		**46,680**	**207**	**544**
3. Rub-Al Khali Basin:				
3.1	Wadi Najran	4,400	125	30
3.2	Other Wadis West	16,500	40	36
3.3	Wadis East	70,000	35	135
Total 3 – Basin		**90,900**	**67**	**201**
4. Arabian-Sea Basin:				
4. A. Draining towards Ramlat Assabatayn:				
4. A- 1.	Wadi Al Jawf	12,000	175	116
4. A- 2.	Wadi Adhanah	8,300	180	87
4. A- 3.	Wadi Harib	2,500	100	14
4. A- 4.	Wadi Bayhan	3,000	125	21
4. A- 5.	Wadi Markhah	4,000	110	24
4. A- 6.	Minor wadis West	3,000	100	17
4. A- 7.	Minor wadis North	7,500	45	19
4. A- 8.	Minor wadis East	5,000	60	17
Total Sub Basin 4. A		**45,300**	**112**	**315**

5.3 Site Evaluation Methodology

5.3.1 Hydrological Evaluation

There are a number of tools available to help determine the hydrology of a potential micro hydro site. These include maps, streamflow and dam's discharges data. These data are available in the National Water Resource Authority (NWRA) database in the

Ministry of Water and Environment (MWE) and the General Departments of Hydrology in the Ministry of Agriculture and Irrigation. In few cases, stream flow measurements may already be available for a particular stream. In other cases, stream flow can be correlated from a nearby stream, which may have similar flow patterns. Actual stream flow measurements should also be undertaken and as much data as possible collected prior to a final commitment to proceed with the measurements.

The discharge from the dam is calculated from the following equation:

$$Q= cd\ Ao(2gh)^{0.5}$$

- where, Q = discharge in (m^3/s), Ao = area of the orifice (m^2), cd = orifice coefficient here is 0.62, g = is gravity acceleration of 9.81 m/s^2, h = initial depth of water (m)

Time of emptying the dams, available time of power in days/year, is calculated from the following equation:

$$T= 2V/Q$$

- where, V is the volume of the dam (m^3).

The discharge of various tributaries was estimated using the standard float method procedure. A float is placed in the stream and timed between two survey points 10m apart. The velocity of flow is determined from the following equation:

Velocity = Distance / Time of travel

The width of the survey station was measured and the depth of flow measure at three points, at one-fifth of the total stream width from both banks and at the mid point.

The average of these gives the depth of flow. The cross-sectional area of each survey point was then determined from the equation:

Area = Width of stream x Depth of flow

The discharge, Q, is determined from equation:

Q = Cross sectional Area x Velocity

5.3.2 Topographical Evaluation

Mapping helps characterize and describe a hydro project site. Maps can be used to locate old access roads, the origin and destination of the stream, the size of the drainage area, and the land title block numbers (which are needed in order to obtain building permits). Maps can provide rough estimates of the length of pipelines and transmission lines, and possible project head. The 1:50,000 scale topographic maps are the first source of mapping utilized, followed by 1:20,000 scale maps, land use maps based on recent air photos. The first two types of maps are obtained from Survey Authority in Sana'a. The 1:1000 scale maps and GPS were used for obtained the Dam's height and site locations. The elevations and coordinates of the potential sites and its tributary were determined using the GPS instrument.

The hydropower potential at each location is estimated from the power equation:

$$P = H \times Q \times g \times e$$

- Where, P = power measured in kW, H = head measured in meters, Q = flow rate measured in cubic meters, g = gravitational constant (~9.8m/S^2), e = efficiency factor (usually ~0.5, i.e. 50%).

5.4 Hydropower Technical Potential

Yemen's hydrological conditions are not, in general, favourable for the development of hydropower stations. The country has a semi-arid to arid climate, low precipitation levels and there is competing use of water with agriculture and domestic water supply. Due to the country wide very low - but punctual - yearly precipitation and the subsequent "rough" behaviour of the rivers and creeks, which means the occurrence of concentrated peak surface flows, the implementation of small run off river hydro power stations is financially not possible.

The study evaluated the prospect of developing hydropower systems in existing dams and major wadis in the country. Dams in Sana'a City, Sana'a and Al Mahwit Governorates were assessed with 16 sites being visited by hydrological expert to verify the resource study calculation results. The resource potential is summarized in Table 5-2. Theoretically, around 1 MW of power could be installed in 21 dams of these Governorates. The availability of power is however very low, ranging from 1 day to 41 days. Technically, it is not possible within reasonable way to use the available water potential for transformation into electrical energy.

Resource evaluation was also undertaken for all major wadis. Sites favourable for constructing hydraulic structures were identified and resource potential was estimated based on the site technical parameters. As shown in Table 5-3, the theoretical hydropower resource potential for major wadis ranges from 12 – 31 MW. Power availability in the proposed sites vary from 50 to 355 days. Nine sites were identified with power availability from 280 to 355 days and total installed capacity ranging from 11 – 30 MW could be technically feasible. The study definition areas of these sites are shown from Figure 5-4 to Figure 5-11.

Development costs of these hydraulic infrastructures, as presented in Table 5-4, were also estimated to be relatively high. Thus, it is not financially feasible to develop the sites mainly for power generation. Multiple water-use projects, based on wide storage reservoirs and shared benefits, are possibly the most appropriate solutions. Drinking water supply, irrigation and hydro power, managed together in one installation, are perhaps the most convenient way. Also shown in the same table is the number of households within the proximity of the proposed infrastructures. In addition to the development costs constraints, the cost of transporting electricity from many of these sites to the nearby villages could be enormous due to sparse distribution of households within the economic distance of the sites.

Table 5-2: Hydropower evaluation results of existing dams in Sana'a and Al Mahwit Governorates

Dam or Site	District	Coordinates		Estimated available gross head (m)	Estimated annual mean flow (m^3/s)	Operation (hr/day)	Estimated theoretical capacity (kW)	Available Time of Power (days/year)	Assessment Result
Jaef Dam	Al-Hareth	433951	1718772	12	0.97	12	57	12	not viable
Mokhtan Dam	Sawan	428220	1700629	10	0.87	12	43	8	not viable
Mosaibeh Dam	Sawan	428315	1700893	14	1.06	12	73	5	not viable
Barian Dam	Sawan	433648	1705044	15	0.58	12	43	1	not viable
Raian Dam	Hamdan	401108	1703376	10	0.61	12	30	4	not viable
Methbel Dam	Hamdan	398836	1699472	7	0.61	12	21	11	not viable
Eram Dam	Hamdan	403092	1709778	15	0.43	12	32	13	not viable
Alljamah Dam	B.Bahloul	434413	1693893	15	0.97	12	71	6	not viable
Ghaiman Dam	B. Bahloul	429477	1687916	5	0.43	12	11	1	not viable
Al-Sabara	Hamadan	403744	1701341	10	0.61	12	30	6	not viable
Bani Nagi Dam	Nihm	444154	1732975	8	0.43	12	17	3	not viable
B.Matar Dam	Bani Matar	392120	1682560	40	1.37	12	269	41	not viable
Artel Dam	Bani Matar			20	0.97	12	55	11	not viable
Almethiah Dam	Haimah			18	0.87	12	49	10	not viable
Salabah Dam	Bani Matar			19	1.06	12	53	19	not viable
Shahekl Dam	Khawlan			24	1.0	12	73	21	not viable
Hiathem Dam	Nehm			10	0.5	12	30	11	not viable
B.Khaiat dam	Tawilah	368231	1710170	15	0.93	12	23	6	not viable
Mamar Dam	Tawilah	396231	1707552	5	0.61	12	45	1	not viable
Hesn Dam	Shibam	375170	1709673	15	0.95	12	61	9	not viable
Total							**1086**		not viable

Table 5-3: Hydropower evaluation results of all major wadis in Yemen

No.	Costal region	Surface Basin / Wadi Catchment	Rough Coordinates (only orientative) [UTM-N]	[UTM-E]	Basin Area [km²]	Aver. Precip. [mm/year]	Estimated Annual Mean flow [m³/s]	Available gross head (estimated)	Operation [hrs/day]	Estimated theoretical capacity [kW]	Estimated Power Plant availability [days/year]	Assessment result
1	Red Sea Basin	Wadi Harad	1822.5	310.5			1	20	15 - 24	98	220	not viable
2		Wadi Mawr	1747	337	8180	430	3.5 - 5.0	100 - 200	15 - 24	2000 - 5900	355	technically feasible
4		Wadi Siham	1656	330	4900	430	2.0 - 3.0	40 - 80	15 - 24	390 - 1180	310	technically feasible
5		Wadi Rima'a	1590	346	2750	580	2.0 - 2.5	50 - 100	15 - 24	490 - 1470	300	technically feasible
6		Wadi Zabid	1550	360	4740	530	4.0 - 5.5	50 - 120	15 - 24	1170 - 3880	355	technically feasible
7		Wadi Rasyan	1483	346	1990	500	0.8 - 1.0	50 - 100	15 - 24	200 - 590	280	technically feasible
8		Wadi Mawza	1470.6	335			1	20	15 - 24	98	220	not viable
9		Wadi Surdud F.Housain	1680.1	330.4	2753	550	3.5 - 4.25	80 - 150	15 - 24	1650 - 3750	353	technically feasible
10	Gulf of Aden Basin	Wadi Tuban	1466.7	474.7	5600	550-1150	3.0 - 4.0	120 - 260	15 - 24	2100 - 6100	300	technically feasible
11		Wadi Suhaibyah	1469	500			0.5	20	15 - 24	49	200	not viable
12		Wadi Bana	1480	530	7800	200-500	5.0 - 6.0	100 - 200	15 - 24	2900 - 7100	350	technically feasible
13		Wadi Hassan	1463	532.5			0.5	20	15 - 24	49	150	not viable
14		Wadi Ahwar	1510	684			0.3	20	15 - 24	29	120	not viable
15		Wadi Mayfa'ah	1580	778			0.25	20	15 - 24	25	110	not viable
16		Wadi Hajar	1763	252			0.3	20	15 - 24	29	150	not viable
17	Arabian Sea Basi	Wadi Al Jawf	1780	480			2	20	15 - 24	196	230	not viable
18		Wadi Adhanah (Mareb dam)	1718	526		200	4	35	15 - 24	392	355	technically feasible
19		Wadi Harib	1625	579			0.1	20	15 - 24	17	50	not viable
20		Wadi Bayhan	1630	625			0.2	20	15 - 24	20	50	not viable
21		Wadi Markhah	1607	618			0.15	20	15 - 24	15	50	not viable

Table 5-4: Infrastructure costs and number of households proximate to the project site

Surface Basin/Wadi Catchment	Estimated cost of infrastructure (million US $)*	Number of households proximate to the project site			
		5 km	10 km	15 km	20 km
Wadi Harad	5.5	17	72	154	241
Wadi Mawr	20.5	15	47	171	383
Wadi Siham	8.1	14	69	169	290
Wadi Rima'a	6.1	35	207	557	988
Wadi Zabid	15.1	26	182	402	721
Wadi Rasyan	11.8	1	2	10	26
Wadi Surdud	10.5	13	70	206	444
Wadi Mawza	5.2	4	13	18	23
Wadi Tuban	8.2	2	6	21	113
Wadi Bana	7.8	0	33	76	115
Wadi Hassan	2.1	47	102	138	165
Wadi Ahwar	2.4	7	21	40	66
Wadi Hajar	2.25	0	0	0	1
Wadi Harib	3.1	23	53	179	206
Wadi Markhah	3.21	5	70	168	195

* for 20 m required head, estimates from Ministry of Agriculture and Irrigation

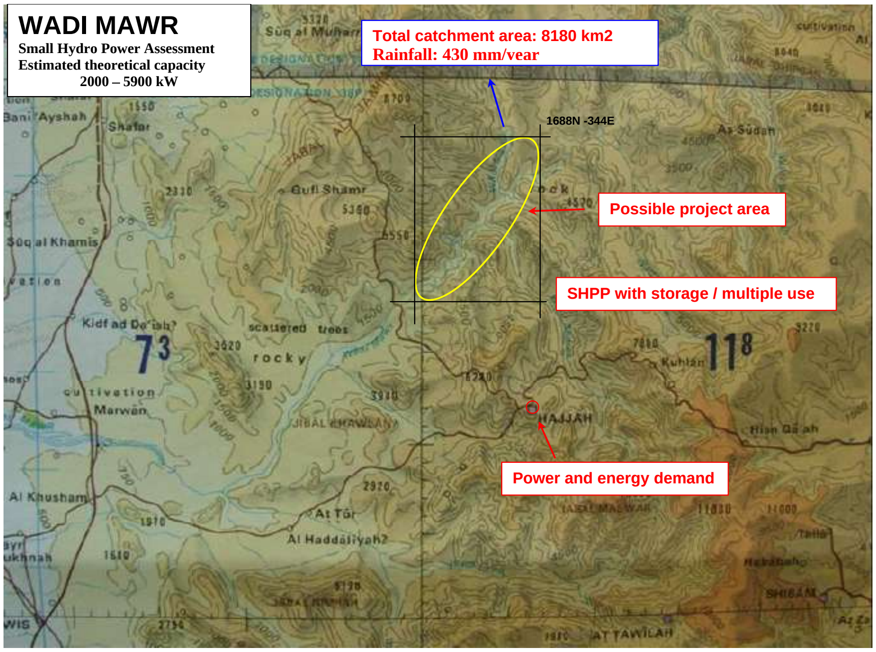


Figure 5-4: Wadi Mawr – study definition area

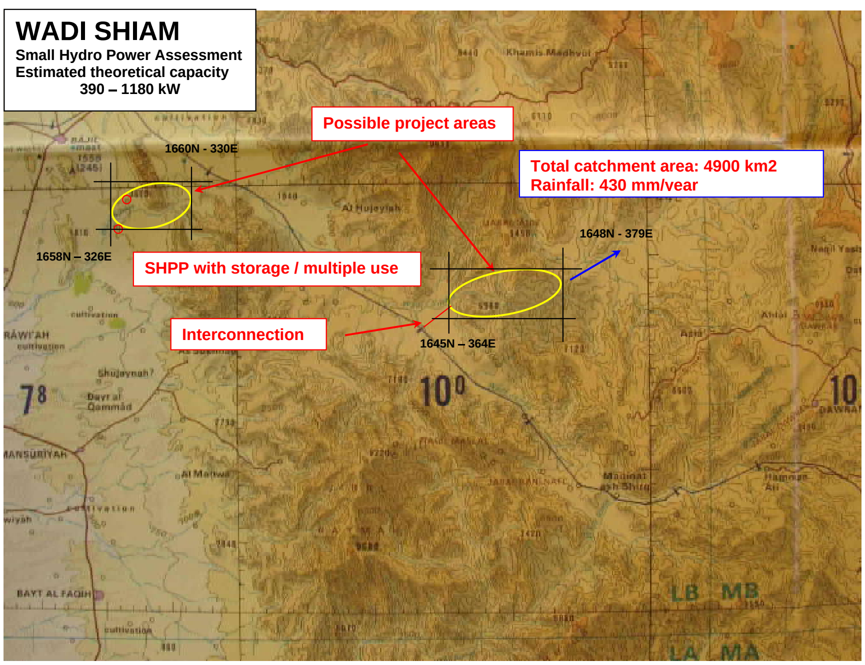


Figure 5-5: Wadi Siham – study definition area

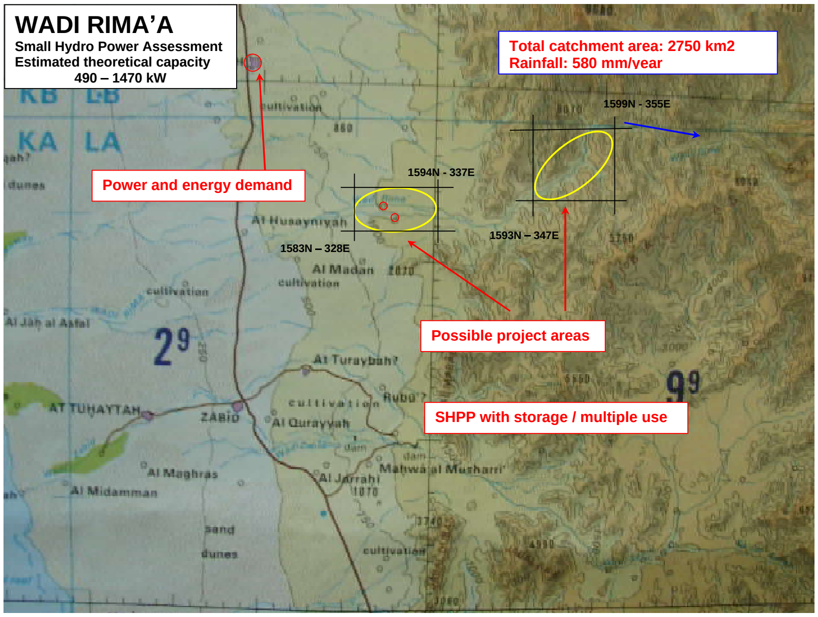


Figure 5-6: Wadi Rima'a – study definition area

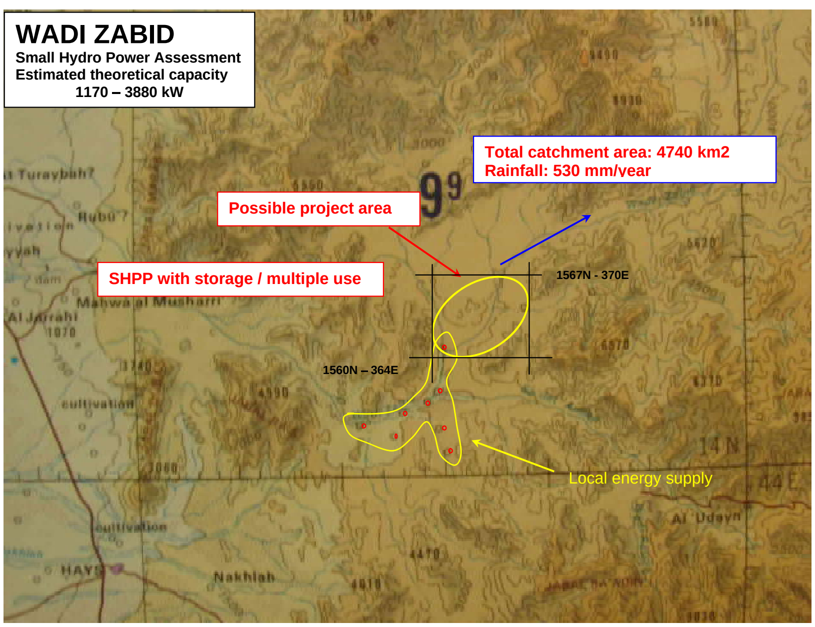


Figure 5-7: Wadi Zabid – study definition area

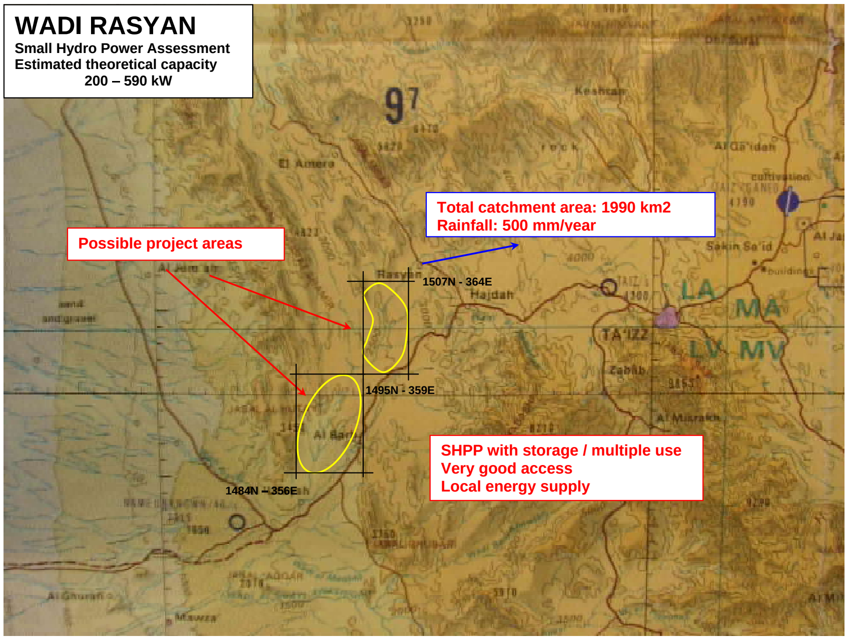


Figure 5-8: Wadi Rasyan – study definition area

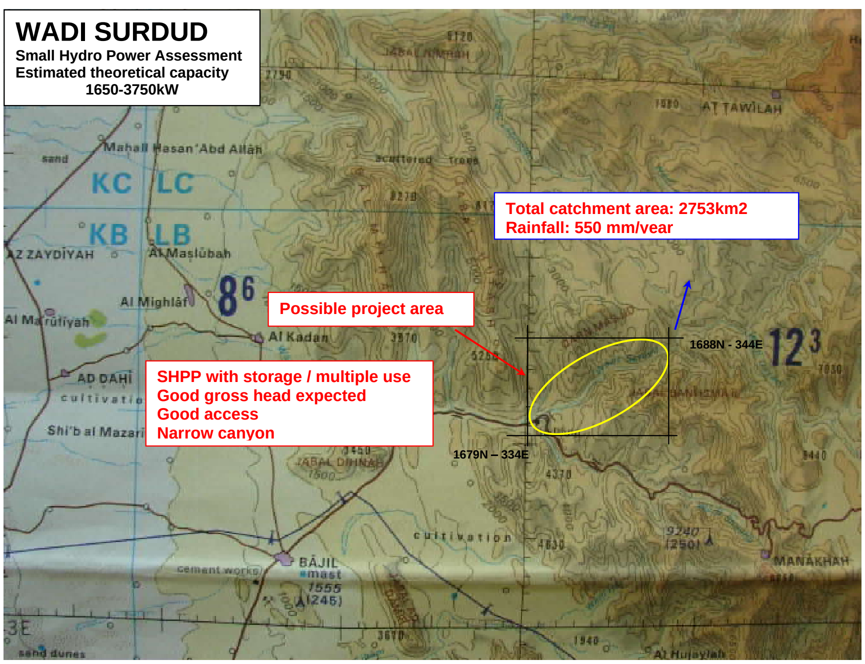


Figure 5-9: Wadi Surdud – study definition area

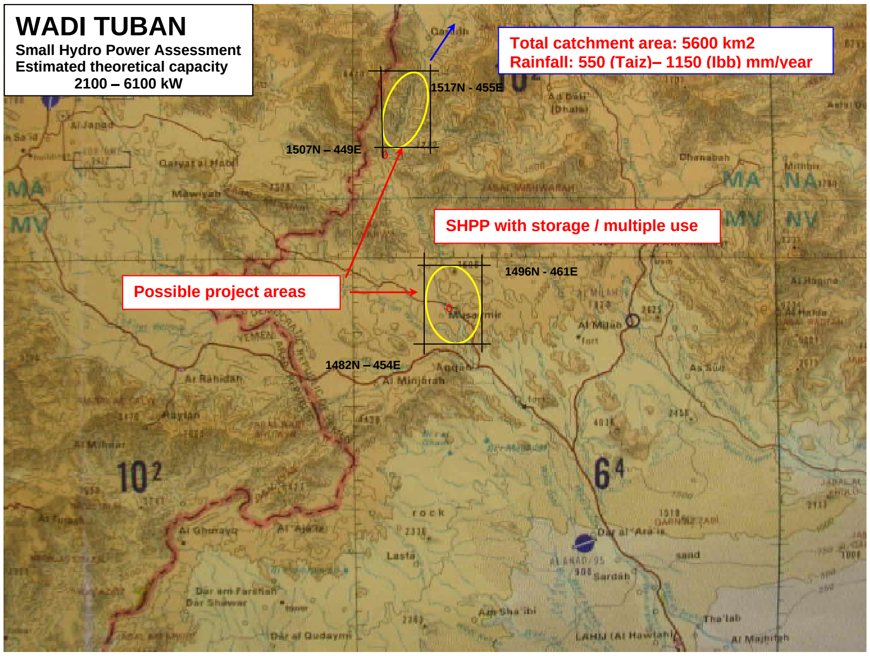


Figure 5-10: Wadi Tuban – study definition area

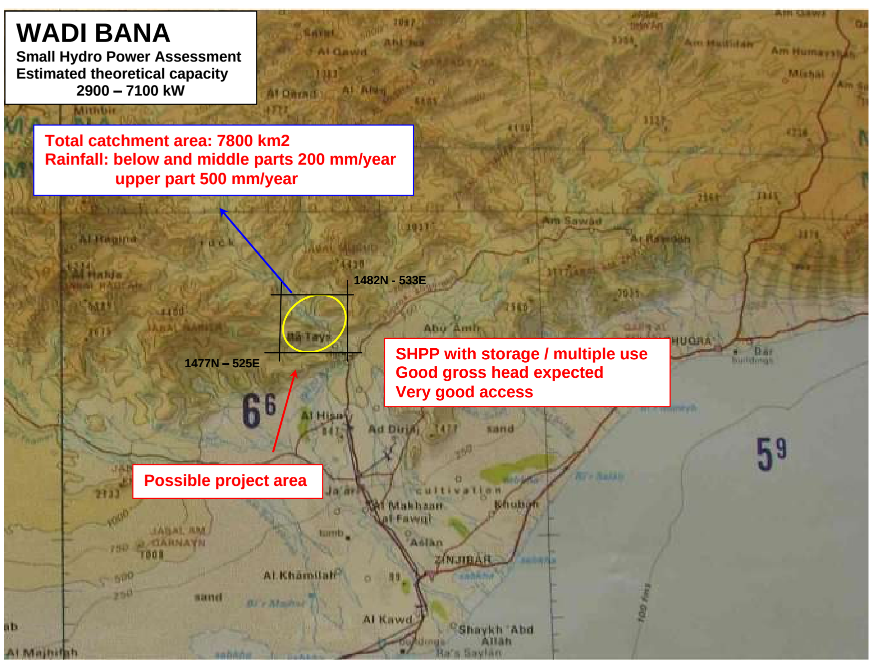


Figure 5-11: Wadi Bana – study definition area

6 Biomass and Waste Energy Resource Assessment

6.1 Biomass and Waste Resource Assessment Methodology

Yemen is an agricultural country with vast agricultural resources. Agriculture is still the mainstay of the economy. The arable land for agriculture is however very limited due to scarcity of rainfall and water resources. Land and water resources are already used intensively for food production and other activities. The biomass potential for energy production is thus limited to residual products from agriculture, animal husbandry, forestry as well as municipal solid waste and waste water.

Various types of biomass for energy production in Yemen were assessed. Biomass residues from agricultural crop, animal, forestry and municipal wastes were investigated. For thermo-chemical conversion, the potential is calculated based on the calorific value of the biomass. In the case of bio-chemical conversion, the calculation is based on the rate of biogas yield of different substrates.

6.2 Biomass-to-Energy Conversion Technologies

Biomass has been used by mankind from its very beginning, and wood still is the most important cooking fuel worldwide. Through the depletion of fossil fuels and the impact of the corresponding CO_2 emissions on global warming biomass has gained new interest and innovative developments are taking place on all levels from biomass production to conversion technologies.

Figure 6-1 shows the most important paths from biomass resources to energy conversion. The following subsections describe the following main conversion pathways: direct combustion of biomass, and anaerobic digestion.

6.2.1 Direct combustion

Direct combustion is the most important way world wide to produce electricity and heat from biomass. Biomass is burned directly to produce hot water or steam. Technical devices are widely distributed with thermal capacities ranging from a few kW in household stoves up to heating plants with several tens of MW. The generated heat can be used directly for household (e.g. cooking) or industrial applications (e.g. process heat), or for electricity production. Thermodynamically, the highest process efficiencies are obtained if both heat and electric power are generated and used in one process.

The conversion efficiencies vary from 8 to 18 percent for simple stoves used traditionally in developing countries up to approximately 90 percent for modern heating or combined heat and power plants.

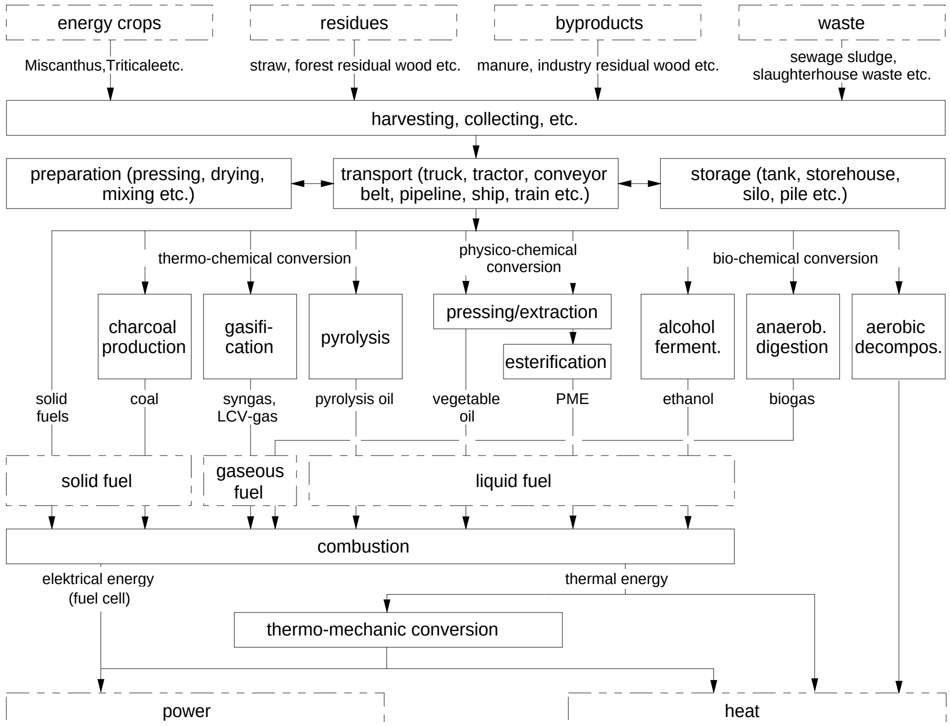


Figure 6-1: Options for biomass energy combustion

For electricity production, different technologies are available, as described in the following:

- Conventional water/steam cycle. Rankine cycle operated with a (continuous) turbo engine, i.e. a steam turbine. By far the most wide-spread technology for electricity generation, both in industrial and developing countries. Overall process electric efficiencies vary from around 10 percent for small steam turbines with simple blade design or single stage (approximately 150 kW up to 5 MW) up to around 30 percent and above for plants with 15 MW and more, where more sophisticated heat exchanger and steam turbine technologies are applied. Although direct combustion followed by a conventional steam cycle is up to now the most widely applied process world wide, there are several disadvantages related to its application arising especially in developing countries: i) at small sizes (<10 MW), electric efficiency decreases considerably, ii) steam/water cycle plants should operate in almost continuous operation. If there is only very low power base load required, as often the case in mini-grids, or there is no grid at all, this technology is not suitable, iii) considerable experience is required for operation and maintenance.
- Steam (piston) engines. Rankine cycle operated with a (discontinuous) reciprocating engine. Available in the range from 25 kW to 1500 kW, with efficiencies around 10%. A Spilling engine reacts insensible to fluctuating steam conditions, can operate with saturated steam and additionally its efficiency remains almost constant under partial load operation.

- Organic Rankine Cycle (ORC). The Organic Rankine Cycle (ORC) is similar to the cycle of a conventional steam turbine, except for the fluid that drives the turbine, which is a high molecular mass organic fluid. The selected working fluids allow to exploit efficiently low temperature heat sources to produce electricity. The typical range of power output per unit is from few kW up to 3 MW electric power.
- Stirling process. An indirectly fired engine with a closed gas volume as working medium. This process is in particularly interesting for developing countries because of its simplicity. This is of significant advantage for very small installations (3 to 50 kW). However, in spite of the interesting concept and high status of development, the Stirling engine is still produced in small series only.

6.2.2 Anaerobic Digestion (Biogas Generation)

6.2.2.1 Basic process

During anaerobic digestion, organic material is decomposed in an oxygen-free (= anaerobic) atmosphere by bacteria that produce a gas containing approximately two-thirds methane (CH_4) and one-third carbon dioxide (CO_2) plus some impurities, after water vapour is condensed. Such decomposition occurs in nature, for example at the bottom of lakes within the sediments containing organic material and in the stomach of cattle.

Well-suited for such an anaerobic digestion are agricultural residues (e.g. liquid manure or dung or crop residues), residues from the food processing industry (e.g. waste water, slaughterhouse residues), and sewage sludge. In some cases, the digestion of the residues is the primary aim. Typical feedstock for biogas production is organic material available at low (or zero) costs and high water content (i.e. in most cases significantly more than 90% water). The only type of biomass that cannot be digested is lignin-containing biomass such as wood.

Anaerobic digestion also is the process that causes the generation of landfill gas in landfills and waste dumps. Accordingly, landfill gas and biogas are quasi identical, differing mainly with respect to their impurities and trace components.

6.2.2.2 Utilization of products

The lower heating value of biogas which depends mainly on the methane content ranges from 14 to 28 MJ/Nm^3. Biogas can be used as cooking fuel, in gas lamps for lighting and from larger installations as fuel for gas engines for generation of mechanical power or electricity in a gas-Otto-engine or diesel engine.

The digested residues from the reactor have to be removed and can be used as fertiliser with better properties (hygienic and fertilising) than the original feedstock itself. Since biogas technology helps to close the nutrient cycle, it is of increasing importance in environmentally sound waste management options. However, depending on the growth period, a seasonal storage is needed in order to allow an efficient utilisation of the fertiliser.

6.2.2.3 Operation of a biogas plant

The operation of a biomass plant requires a considerable amount of care and experience to ensure optimal process conditions (temperatures of 28 to 35°C, sedimentation of mineral contaminants, break-up of the material into small pieces access of the bacteria to the organic material, slurry with a water content of more than two-thirds, thorough and continuous mixing) so that gas yields are maximised. Nevertheless, small and simple plants can be operated by non-professionals. The feedstock is pumped in or given in by hand into the biogas container or reactor where the anaerobic fermentation takes place.

Especially for its use in developing countries, biogas technology has the following advantages:

- High compatibility towards fluctuations of demand: in periods with biogas production exceeding the consumption (i.e. at night), the biogas is stored in the fermenter. This is especially relevant for stand-alone plants or mini grids.
- Relatively low specific investment needed for a simple biogas plant can be as low as 100 Euro/kW or even lower (high efficiency biogas plants in Europe: around 4000 – 4500 Euro/kW at a size of 500 kW).

Usually fuelled by feedstock that has to be disposed of anyway, additional benefits of biogas digestion arise from sanitation / waste elimination.

6.2.2.4 Existing biogas plants in Yemen

In several developing countries in Asia, especially in India, Nepal and China, the use of biogas for household cooking and lighting is common practise in some rural areas, usually on a community-scale level.

In Yemen, previous experience with the use of biomass for energy generation is restricted to a number of small plants for producing biogas, most of which were set up in the 1980s as part of a scheme promoted by the United Nations. Another biogas project was established in Al-Habeel in Lahj Governorate in 1990's by the MoE and the assistance of ESCWA organisation implementing 22 digesters (family size).

Recently family size biogas digestors are installed with support of CARE, an international non-governmental organization. The cost per system is between 90,000 – 120,000 YER (400 – 525 Euros).

6.2.3 Biofuels

In general, the production of three types of biofuels has been realised on an industrial scale (Table 6-1). Biofuels usually are generated from large scale plantations of crops specifically suited for biofuels production (energy crops). For example, for a small ethanol factory, more than 1000 ha land have to be cultivated and irrigated. Ethanol producing factories cost several million US$ even in a small scale of 10 m^3/h. Adding 1000 – 2000 US$/ha for plantation irrigation and for other infrastructure, ethanol production can only be introduced with an investment of about US$ 10 million.

Given the high investment costs, the scarcity of water in Yemen and the lack of agricultural land, the production of biofuels is not further assessed.

Table 6-1: Biofuel applications

Biofuel Type	Production	Use
Plant Oil	Mechanical or chemical extraction (or combination of both) from oil containing plants such as rape seed, Jatropha, Oil Palm	Substitute for diesel fuel in transport sector or small scale electricity generation after slight technical modifications, as well as cooking fuel
Biodiesel	Produced from plant oil via (large-scale) transesterification and refining	Sale to the transport sector as a direct substitute for diesel fuel
Bio-Ethanol	Anaerobic fermentation of sugar in a water solution; distillation; rectification for high purity. Either produced directly from sugar containing biomass such as sugar cane, or indirectly from starch containing biomass such as cerial or corn after polysaccharide decomposition.	Substitute for gasoline either in a mixture (<5% without modification) or pure in modified gasoline engines. Also used as cooking fuel.

6.2.4 Gasification

Gasification has principal advantages compared to direct combustion since solid biomass is transferred into a gaseous fuel, which can be burned in internal combustion engines with high efficiencies. Thus, no water/steam cycle is required, which is of particular interest for small scale installations.

However, a cost and energy efficient cleaning of the generated gases is still problematic. It has been technically realised in coal and refinery residues gasification installations of several hundreds of MW syngas capacity, but no small (< 10 MW) installation in known which runs successfully an internal combustion engine for a longer period. Until these problems are not solved, gasification technology is not regarded as proven and is therefore not further considered.

6.2.5 Biomass carbonization

Carbonisation as well is a way to improve combustion properties and transport efficiency by driving out the water. Mainly wood is used, but several crop residues can be carbonised as well. For small sized crop residues, the carbonisation step should be followed by briquetting for better handling and transport ability.

The industrial carbonisation might be advantageous for charcoal production from wood since it is less environmental pollutant than traditional kilns. However, since customers did not accept carbonised briquettes (made of cotton stalks, with binder molasses, Sudan) and no additional biomass resources were made accessible, these technologies are not taken into further account.

6.2.6 Waste incineration

Incineration of municipal waste is an environmentally acceptable way but is technically demanding, thus expensive. It is more complex than the combustion of pure biomass. The amount of energy generated is by far not enough to compensate expenditures. The reason why increasing shares of municipal waste are being incinerated in industrialised countries is not generation of energy, but reduction of waste and inertisation with the aim of a safe landfilling of the residues.

The lack of profitability, the high investment and the complex technology are reasons why incineration of municipal waste is not regarded as suitable technology for energy generation for Yemen.

6.2.7 Landfill gas utilization

Landfill gas is generated naturally in every dump and landfill by anaerobic digestion. The amount of gas produced depends on the extent of the anaerobic zone and other factors such as moisture content and temperature.

Landfill gas consists of the bulk components carbon dioxide and methane, but also contains a great amount of partly harmful trace components. The main aim of combustion of the landfill gas is to reduce the negative effects on the environment and human health that arise from properties such as explosivity, bad odour, ecotoxicity, and the high global warming potential due to the methane content.

In order to collect the landfill gas, a capping of the landfill and the installation of a collecting system is required, usually consisting of perforated tubes inside the landfill. The tubes are connected with a blower that sucks the gas out of the landfill and blows it into an engine (gas-Otto-engine, diesel engine) or a boiler. The tubes can be placed vertically with a distance of about 30 m. Landfill gas has to be cleaned carefully prior to combustion in engines since it contains several components which damage the engine. The specific investment costs to use landfill gas are high, but much lower than for the option of direct combustion.

6.3 General Overview of Biomass in Yemen

6.3.1 Application summary

The resources for the energy potential from biomass in Yemen can be classified in a systematic approach into six main groups depending on their origin as shown in Table 6-2, showing also the possible technologies of utilisation.

This section screens the biomass resources and assesses their potentials for energy generation. The different types of residues are discussed and the opportunities to use them technically for energy generation are analysed. The relevant opportunities (high potentials) among the existing biomass resources are identified.

Table 6-2: Biomass applications in Yemen

	Biomass combus-tion	Biogas	Biofuels	Landfill gas	Waste inciner-aton	Carbo-nisation	Gasi-fication
Energy crops	X		X			X	X
Agricultural crop residues	X	X					
Animal husbandry residues	(X)	X					
Forrestry biomass residues	X					X	X
Municipal waste				X	X		
Waste water		X					

6.3.2 Physiographic and agro-ecological zones

Biomass resources depend essentially on other natural resources like, the following:

- Soil fertility
- Precipitation, other water resources
- Ambient temperature
- Solar radiation

In most parts of Yemen precipitation and the availability of surface and groundwater is the limiting factor to the size of the biomass stock and its productivity

The following map (Figure 6-2) shows the average length of the growing period for rain fed agriculture. As all areas with significant growing period for rain fed agriculture is found in the Mountain Area, the major biomass resources will be found also in this part oft the country. The bordering plains and major wadis are zones of irrigation agriculture.

6.3.3 Physiographic and agro-ecological systems

Yemen is characterised by varieties of environmental zones. Since early 80s there were many attempts to classify the agro-ecological zones, occasionally by using the physiographic features and, time to time, by using landforms and climatological characteristics. The predominant distinction has given by Bamatraf A. M., 1994 as follows ().

- Coastal plains in the West and South
- Yemen Mountain Massif
- Eastern Plateau and Desert
- Islands

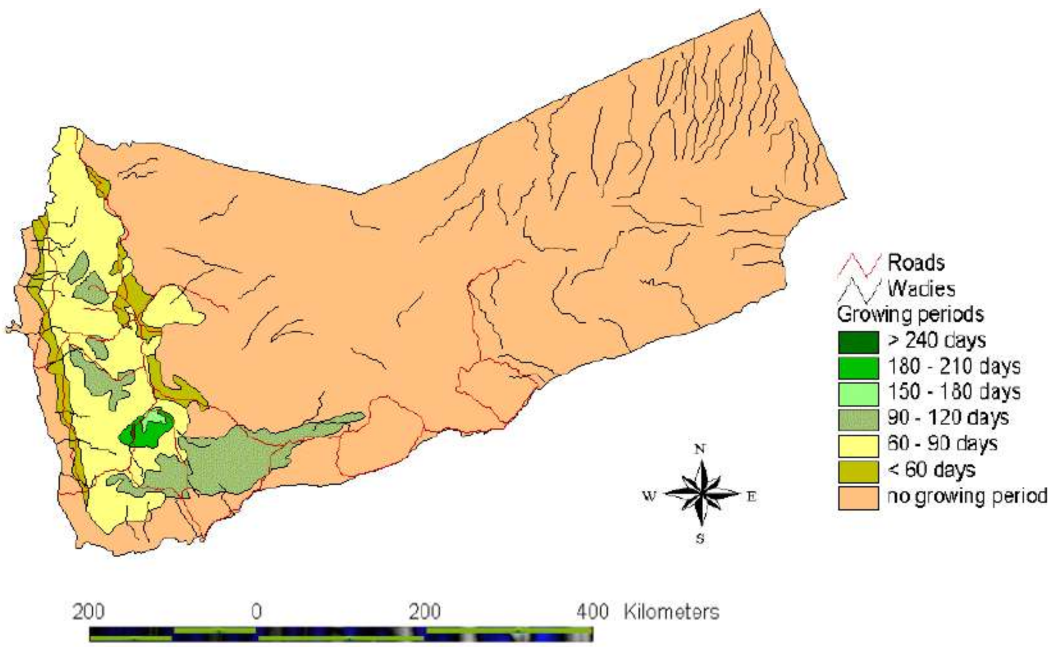


Figure 6-2: Length of growing period for rainfed agriculture in Yemen

Figure 6-3: Main classification of agro-ecological zones in Yemen

6.3.3.1 The Coastal Plains in the West (Tihama) and South

The Plains are located in the west and south-west and are flat to slightly sloping with maximum elevations of only a few hundred meters above sea level. They have a hot climate with generally low to very low rainfall (semi-arid subtropical < 50 mm/year) (Table 6-3). Nevertheless, the Plains contain important agricultural zones, due to the numerous wadis that drain the adjoining mountainous and hilly hinterland supplying ground water and surface water for irrigation

The southern Coastal Plains region includes the low coastal plains facing the Gulf Aden and the Arabian Sea making up a coastal strip extending to the Omani border in the east towards the southwest to Bab al Mandab. It starches over an area 2000 km long and 20-60km wide, with an altitude ranges 0-500m above sea level. Many seasonally flowing wadis dissect the region. An arid sub-tropical climate dominates the region with average annual rainfall in the range of 50-300 mm.

Table 6-3: Coastal plains physiography and ecology

Physiographic unit	Area [km²]	% of Total	Ecological Zones Vegetation	Predominant soil Types	Major Geological Formation
Western Coastal Plain (Tihama)	20,300	3.9	Arid tropical desert; sand dune vegetation of the Red Sea; Acacia spp.	Torrifluvents, Torripsamment; Ustifluvents, ustipsamments, Ustipsamments, salortheds.	Quaternary alluvial deposits.
Southern Coastal Plain and Foothills	55,000	10.4	Arid tropical; desert and semi desert vegetation absent by sea-saline grasses; vegetation on hills; water cockles in wadi.	Deep to shallow calcareous sandy to loamy; saline in coastal area; light yellowish in eastern part.	Hills, sand dunes and sheets; grace and sandy to loamy plains

6.3.3.2 The Yemen Mountain Massif

This massif constitutes a high zone of very irregular and dissected topography, with elevations ranging from a few hundred metres to 3760 m above sea level (Table 6-4). Accordingly, the climate varies from hot at lower elevations to cool at the highest altitudes. The western and southern slopes are the steepest and enjoy moderate to rather high rainfall, on average 300-500 mm/year, but in some places even more than 1000 mm/year. The eastern slopes show a comparatively smoother topography and average rainfall decreases rapidly from west to east.

This region is divided into three main catchments, the western slopping towards the Red Sea, the southern towards the Gulf of Aden and the north-eastern towards the empty quarter (Al Rub al-Khali). The climate is characteristic of the semi-arid tropics, with limited areas of dry temperate intermountain plains at altitudes above 2000m.

Table 6-4: Mountain Massif physiography and ecology

Physiographic unit	Area [km²]	% of Total	Ecological Zones Vegetation	Predominant soil Types	Major Geological Formation
Southern Uplands	12,000	2.3	Semi-arid subtropical mountains; Acacia spp., Juniperus spp., Euphorbia scrub.	Ustifluvents; ustiorthents; torriorthents;rock outcrop.	Tertiary and quaternary volcanics.
Highlands slopes	45,500	8.6	Arid to semi arid temperate mountains, Acaciaspp., juniperus spp., .	Rock outcrop; ustiorthents.	Tertiary and quaternary volcanics; sedimentary rocks; quaternary alluvial deposits.
Midland slopes	39,200	7.4	Arid subtropical mountains; Acacia spp., weed rich vegetation.	Rock outcrop; ustiorthents; torripsamments; calcareous loamy and sand plains.	Tertiary and quaternary volcanics; Precambrian shield; sedimentary rock.
Middle Mountain Highland	84,500	16.0	Arid subtropical; vegetation nearly absent, except some in wadi and on soil and rocky plains.	Sandy to loamy in the western part, and calcareous to loamy in the eastern part.	Volcanic rock basement in the western part, and calcareous rocky plains in the eastern part; sandy to loamy sedimental complex in wadi.
High Mountain	21,000	4.0	Arid subtropical; vegetation nearly absent; some trees; grasses after rainfall.	Sandy to loamy in the west, and calcareous sandy to loamy in the east.	Hills, volcanic rocky plains in the west and calcareous rock in the east; sandy loam in wadi.

6.3.3.3 The Eastern Plateau and Desert

This region covers the eastern half of the country. It is bordered by the mountains zone to the west, the southern coastal plains to the south. Elevations decrease from 1200 - 1800 m at the major watershed lines to 900 m on the northern desert border and to sea level on the coast. The climate in general is hot and dry, with average annual rainfall below 100 mm, except in the higher parts. An arid sub-tropical climate dominates its major agricultural lands (Table 6-5). Floods following rare rainfall may be devastating.

Its northern zone is dominated by the Rub Al Khali desert, which extends far into Saudi Arabia and the Ramlat As Sabatayn, a sand desert. Rainfall and vegetation are nearly absent, except along its margins where rivers bring water from adjacent mountain and upland zones.

Table 6-5: Eastern Plateau physiography and ecology

Physiographic unit	Area [km²]	% of Total	Ecological Zones Vegetation	Predominant soil Types	Major Geological Formation
Eastern and North-eastern Desert plateau.	250,200	47.4	Arid subtropical desert; sand dune vegetation; absent vegetation except for grasses after rainfall.	Torriorthents, torrifuvents; torripsamments, calcareous loamy and sandy plains.	Quaternary alluvial deposits; sand sheets and dunes; calcareous sedimental rocky; sand plains.

6.3.3.4 The Islands

The most important of all the islands is Socotra, where more exuberant flora and fauna can be found than in any other region in Yemen.

6.3.4 Farming system

Yemen's agriculture has flourished for over three thousand years because of the variety of ways in which limited water resources have been used for irrigation and water supply. Despite complex methods, Yemeni farmers practice an integrated crop animal system in which they produce cereal summer crops to feed their animals and use the cow manure to improve the soil fertility of their land. Due to this system livestock is of significant size despite the limited resource of arable land. Nevertheless the volume of crop and animal residues without use is in general highly limited.

6.4 Energy Crops

The term energy crops refer to non food agricultural or non timber forestry plantations to harvest energy rich products like the following:

- Wood / lingo-celluloses
- Oil seed
- Starch and sugar containing plant parts (grains, tubers, stem, shoots, etc)

Energy crops are used to serve as fuel (wood) or to be processed into fuel (alcohol, vegetal oil, bio diesel, synthetic biomass-to-liquid fuels, bio gas/methane, charcoal). Energy crops might be different from species used for other purposes, but generally just the purpose of production changes. Typical examples for species used for energy crop production area:

- Oil Palm (elaeis guineensis)
- Physic Nut (jatropha curcas
- Eucalyptus (eucalyptus L.)
- Elephant Grass (miscanthus x giganteus)
- Sugar cane (saccharum L.)
- Castor Oil Plant (ricinus communis L.)
- Maize (zea mays)

Currently no crops are grown in Yemen with the primary purpose of supplying fuel or energy. The only exemption is trees in woodlands, agro-forestry and forests are managed to provide also traditional fuels like fire wood and charcoal. This kind of multi purpose use of forest based resources is generally not subsumed under the term energy crops.

Energy crops of course could be produced in Yemen, under rain fed as well as irrigated conditions. But given the limited availability of arable land, the scarcity of precipitation and surface as well as ground water resources opportunity costs will be much higher than the return from fuel or energy production. Currently only in the humid tropics and sub-tropics energy crops are grown at competitive prices.

In the case of Yemen other renewable energy sources like wind and solar will be more cost effective. Energy crops will therefore not be analyzed further within this study.

6.5 Residuals from Primary Production in Agriculture and Animal Husbandry

6.5.1 Agriculture

6.5.1.1 Methodology and assumptions

Yemen has an extremely diversified an adapted agriculture. All agricultural activities are concentrated to the regions with sufficient precipitation in the highlands and mountains, to the coastal plains and some groundwater fed wadies (e.g. Hadramout).

The base data for this study are the following:

1. Agricultural Statistics Year Book 2004, Republic of Yemen, MoAI, published May 2005
2. Agricultural Statistics Pamphlet 2004, Republic of Yemen, MoAI, published May 2005

The data has been complemented by several interviews:

1. Al-Shami, Director of FAO in Yemen
2. Jamil Al-Mamari, Directorate General of Animal Resources, Responsible for the statistical data on animal production, MoAI
3. Mohammed Noira, General Manager of the Agricultural Statistics, MoP
4. Mr. Anwar A. Alaziz, Head of Climate Change EPA

All data available to the consultant was on a Governorate level, therefore no disaggregation to District level was not possible. Whenever available, additional information on the localization of the resource is given.

The analysis will follow the classification of the agricultural production, given in the Agricultural Statistics Year Book defining 6 classes of products (Table 6-6). The underlined crops are taken into account. The remaining crops have a negligible contribution to the biomass energy balance.

Table 6-6: Classification of crops in Yemen

Cash crops	Pulses	Fruits	Vegetables	Cereals	Fodder
Qat	Chick Peas	Grape	Potatoes	Sorghum	Grasses
Tobacco	Lentil	Papaya	Tomatoes	Maize	Sorghum
Cotton	Dry Haricot Beans	Apricot	Onion	Millet	Alfalfa
Sesame	Broad beans	Peach	Okra	Wheat	
Coffee	Fenugreek	Pomegranate	Cucumber	Barley	
	Peas	Banana	Carrot		
	Other legumes	Orange	Green Haricot Beans		
		Lemon	Parsley		
		Fig	Jaws mallow		
		Quince	Squash		
		Mandarin	Capsicum		
		Mango	Eggplant		
		Guava	Radish		
		Dates	Garlic		
		Apple	Cabbages		
			Pepper		
			Watermelon		
			Sweet melon		

6.5.1.1.1 Cash crops

Qat is currently the major cash crop in Yemen. As a shrub or a small tree it grows as a perennial crop to a height of up to 5-7m before it gets completely cut and replaced.

The woody branches are used as fire wood. As its growth is slow due to the constant cutting of twigs with fresh leaves, the annual woody increment in biomass is negligible. Qat is therefore not taken into account in the biomass resource assessment.

Figure 6-4: Qat and sorghum in an irrigated plantation (Al-Mahwit Governorate)

Tobacco is planted on 5000 to 8000 ha. The residuals are negligible as they neither used as fodder nor will be of importance to the biomass energy balance due to their very low content of celluloses. Therefore tobacco is not considered in the biomass energy balance of this study.

Cotton is in its extension of plantation more important with around 20 – 30 thousand hectares. Again, stem and leafs are due to their very low content of celluloses are negligible. The seeds obtained in a central processing plant generally are used to extract edible oil or as protein and fat rich animal fodder. Therefore cotton is not considered in the biomass energy balance of this study.

Sesame has a fibre (celluloses) rich stalk. It is used as fodder and could be also used for energy purposes and thus is considered in the energy balance.

Coffee is a slowly growing small bush. The annual woody increment in biomass is negligible. The so called coffee cherry consists of the bean ("coffee bean") and the flesh of the fruit. In other countries this remainder is not utilized, whether in Yemen it is dried an sold to prepare a beverage.

6.5.1.1.2 Pulses

All residuals from the pulses production are considered indirectly in the biomass energy balance. As their straw is a good fodder and of higher nutritious value than stalks of cereals it is commonly used in animal husbandry. It will thus increase the amount of residuals from cereals that will be available for energy purpose.

6.5.1.1.3 Fruits

Fruits are grown on about 800 – 900 km² in Yemen. Around 90% of this area is for perennial fruits growing as fruit trees or shrubs and thus developing woody biomass. As the related area (700 – 800 km²) is very small compared to forests and tree covered land (24.000 km²) their contribution to the biomass energy balance has been neglected. The remaining 100 km² (10.000 ha) are used for banana and papaya production, which were also not considered in the energy balance as no data and experience with banana and papaya stems for biomass energy purposes (e.g. bio gas fermenters) were found in the literature.

6.5.1.1.4 Vegetables

Residuals (stem, leaf, roots, etc.) from vegetables are generally very low in volume compared to the production volume and also low in its fibre/celluloses content and thus will not contribute significantly to the biomass energy balance. They have therefore been neglected.

6.5.1.1.5 Cereals

All major cereals in Yemen (Sorghum, Maize, Millet, Wheat, Barley) have been taken into account. As residuals from the harvest (stem, leaf, roots, etc.) also are used as animal fodder a detailed fodder balance taking into account the fodder demand of the livestock, all fodder produced and all harvest residuals from cereals, pulses and sesame has been elaborated on a governorate level. Assuming that the use as fodder is preferential due to the nutritious and monetary high value of animal production only the remainder will be considered as available for energy purposes.

Figure 6-5: Rainfed sorghum plantation in Al-Mahwit Governorate

6.5.1.2 Assessment results

Under the assumption of the following residue/grain ratios and 20% of collection losses the following amounts of biomass have been available in Yemen over the last 5 years. The grain ratios are based on publications of FAO. They give a good estimate for agriculture with lower per hectare yields (1–2.5 grain/seeds per hectare). The grain ratio used in the study is the following:

- Sorghum - 2.5
- Maize - 2.5
- Millet - 2.5
- Wheat - 1.75
- Barley - 1.75
- Sesame - 1.75
- Pulses - 1.5

The total residue production is given in Table 6-7.

Table 6-7: Gross volume of residues (without deducting the portion used for animal fodder), tons

Governorate	2000	2001	2002	2003	2004	average	standard deviation
Hodeidah	217,630	223,102	188,312	150,272	140,293	183,922	66,176
Sana'a	120,596	132,916	106,492	71,936	74,181	101,224	34,539
Dhamar	114,363	126,149	102,439	72,501	72,875	97,665	34,706
Ibb	97,260	104,899	92,928	73,391	51,126	83,921	28,502
Taiz	59,160	59,864	46,335	32,132	36,424	46,783	18,397
Mareb	88,538	81,939	61,290	52,633	13,882	59,657	25,568
Hajiah	22,402	25,090	20,856	16,548	66,531	30,286	13,861
Al-Beida	15,473	16,044	12,270	9,205	16,794	13,957	4,984
Sadah	33,127	31,107	26,510	21,167	12,853	24,953	9,190
Al-Mahwit	13,519	15,105	13,001	10,281	13,167	13,015	4,384
Lahj	5,683	6,431	5,340	5,045	10,613	6,622	2,477
Abyan	6,349	7,281	5,869	5,207	25,320	10,005	4,597
Hadhramout	14,712	16,350	13,926	12,102	18,233	15,065	5,839
Al-Jawf	70,098	73,003	67,130	61,715	43,297	63,049	26,365
Shabwa	5,682	6,145	5,106	4,534	8,206	5,935	1,949
Al-Mahara	326	361	269	258	367	316	128
Aden	294	258	170	172	617	302	135
Amran	0	0	0	0	45,398	9,080	8,082
AL-Daleh	0	0	0	0	15,078	3,016	2,790
Sana'a City	0	0	0	0	2,118	424	385
Raimeh	0	0	0	0	7,257	1,451	1,373
Total	885,212	926,046	768,245	599,100	674,629	770,646	246,945

Table 6-8: Balance of crop residuals and forage production versus biomass demand for animal feed, tons

Governorate	2000	2001	2002	2003	2004	average	strd. deviation
Hodeidah	386,618	387,571	294,827	253,929	266,563	317,901	58,028
Sana'a	-4,140	-4,643	105,154	68,300	36,323	40,199	42,428
Dhamar	-19,613	-13,633	-58,459	-90,786	-75,916	-51,682	30,458
Ibb	-124,789	-127,093	-110,687	-132,946	-140,789	-127,261	9,962
Taiz	-102,413	-109,014	-155,689	-171,734	-106,257	-129,021	55,424
Mareb	79,864	70,208	62,630	52,216	-1,877	52,608	28,712
Hajiah	-55,871	-59,417	-154,784	-161,610	-108,530	-108,042	45,035
Al-Beida	-49,439	-52,532	-55,358	-59,814	-58,355	-55,100	28,916
Sadah	-36,003	-41,515	-119,206	-126,975	-77,249	-80,190	49,014
Al-Mahwit	35,198	34,883	5,367	1,484	-39,602	7,466	19,815
Lahj	-26,030	-30,152	16,942	14,130	20,134	-995	15,737
Abyan	13,954	10,748	18,087	15,872	-46,069	2,518	19,341
Hadhramout	-109,737	-117,043	-189,807	-204,961	-195,336	-163,377	90,154
Al-Jawf	125,915	126,047	89,448	84,001	-73,742	70,334	66,142
Shabwa	-25,623	-29,451	-105,180	-107,686	-63,999	-66,388	35,333
Al-Mahara	-77,676	-80,395	-130,670	-132,536	-210,126	-126,281	48,076
Aden	8,691	5,033	20,463	20,391	4,083	11,732	7,977
Amran	0	0	-139,468	-141,173	-56,238	-67,376	53,630
AL-Daleh	0	0	-67,474	-68,907	-43,224	-35,921	27,213
Sana'a City	0	0	-13,192	-13,685	-10,746	-7,525	5,606
Raimeh	0	0	0	0	-24,796	-4,959	6,900
Total	18,907	-30,398	-687,055	-902,491	-1,005,748	-521,357	379,495
	1%	-1%	-24%	-31%	-31%	-19%	

Table 6-8 shows that for most Yemeni Governorates and in sum for the national territory no residuals from agricultural production are available for energy production purposes. It even shows that there is a severe shortage of fodder for the existing livestock, as life stock is underfed by 30% in the last 2 years. This means that eventually the assumed average life weight is to high, or that additional fodder resources are provided, like forage from trees, residuals from the vegetable production or that high quality complementary fodder is provided.

However the result of the analysis is, that only in Hodeidah governorate (Tihama coastal plain) a significant volume of residuals (and fodder) is available. In average over the last 5 years this was around 320.000 tons of dry biomass per year, which corresponds to about 110.000 TOE of energy.

Apparently most of this biomass is exported to other Governorates, as high rates of fodder production indicate, as well as the demand in neighbouring Governorates (e.g. Hajiah, Ibb, Taiz, Dhamar) as well as the road transport to the highlands (Figure 6-6).

The general scarcity of fodder for animals can also be seen from the level of "cleanness" of the fields after harvest (Figure 6-7). Only a minimum of residues are left over. Most of the stalks and leafs are carefully bundled (Figure 6-8) and brought to the homesteads where they serve as a stock of fodder for the livestock kept in the house.

Based on the national balance of crop residues, fodder production and the livestock's fodder demand can be resumed that there are no biomass residuals in agriculture available for energy purposes. This result based on agricultural statistics is supported be evidence from the consultant's visits to the countryside in the mountains and coastal plains as well confirmed by various experts interviewed.

Figure 6-6: Transport of fodder close to Hodeidah Governorate

Figure 6-7: Wheat and barley field after harvest in Sana'a Governorate


Figure 6-8: Bundled crop residues close to homesteads in Al-Mahwit Governorate

6.5.2 Animal Husbandry

This section analyzes dung production from animal husbandry. First, the overall volumes per governorate level are presented then the volumes available on typical farms are studied. In recent years, sheep, goats and chicken production increased significantly to satisfy the growing farm and market demand as well as to improve farmer's income by adding additional value to crop production.

6.5.2.1 Dung production from ruminants

The total annual dung production from ruminants (cattle, sheep, goat and camel) was about 1,370,000 tons in 2004, an average increase of more than 6 percent per year since 1998 (Table 6-9). Almost half of this amount (510,000 ton per year) is produced by cows and cattle. The rate of production increase from these animals is however relatively slow with only 1.7 percent per year (Table 6-10).

To estimate the total available dung for energy generation the following collection factors have been assumed for the different kinds of animals:

- Cow/cattle - 50 percent
- Camel - 10 percent
- Sheep - 20 percent
- Goat - 20 percent

These collection factors reflect the fact that generally cattle are kept confined or semi confined (i.e. confined at night) in contrast to the mostly free ranging camel. Goats and sheep, on the other hand are either free ranging or semi-confined.

Dung production from cattle and other ruminants concentrates primarily on the Governorates Hodeidah, Ibb, Taiz Dhamar, Hajiah and Hadramout. The total amount of dung available is around 425,000 tons in 2004. Available dung volume grew at about 4 percent per year over the last 6 years (Table 6-11).

The primary energy content of the total available dung volume from ruminants corresponds to around 140 tons of oil equivalent or 5,860 GJ per year.

Table 6-9: Dung production from cattle, sheep, goat and camel

	Ruminant livestock dung production [1000 tons dry mass/year]						
Governorate/Year	1998	1999	2000	2001	2002	2003	2004
Hodeidah	109	111	111	116	141	141	169
Sana'a	149	156	156	163	99	101	57
Dhamar	77	79	80	83	93	94	85
Ibb	104	106	112	116	103	105	90
Taiz	78	79	80	84	100	101	101
Mareb	31	31	32	33	26	26	39
Hajiah	61	62	63	66	109	110	101
AL-Beida	37	38	38	40	40	40	38
Sadah	35	36	36	38	71	72	81
AL-Mahwit	22	19	19	20	31	32	24
Lahj	57	63	64	67	44	45	44
Abyan	48	49	49	52	48	49	74
Hadramout	51	52	69	73	99	101	138
AL-Jawf	21	22	23	24	37	38	75
Shabwa	30	31	32	34	66	67	81
AL-Mahara	28	26	26	27	36	36	59
Aden	9	10	9	10	3	3	3
Amran	0	0	0	0	65	66	53
AL-Daleh	0	0	0	0	31	31	28
Sana'a City	0	0	0	0	6	7	7
Raimeh	0	0	0	0	0	0	23
Total	947	967	999	1,045	1,248	1,265	1,372

Table 6-10: Dung production from cow and cattle livestock

	Dung [1000 tons dry mass/year]						
Governorate/Year	1998	1999	2000	2001	2002	2003	2004
Hodeidah	74	74	74	78	83	84	106
Sana'a	76	81	81	85	50	51	25
Dhamar	52	53	54	56	59	60	58
Ibb	83	83	84	87	77	77	70
Taiz	60	61	62	65	62	63	64
Mareb	6	6	6	6	2	2	3
Hajiah	39	40	41	43	47	48	50
AL-Beida	12	12	12	13	7	7	7
Sadah	22	22	23	24	29	30	30
AL-Mahwit	17	15	15	16	21	22	18
Lahj	24	26	27	28	16	16	14
Abyan	6	6	6	6	5	5	8
Hadramout	1	1	17	18	4	5	5
AL-Jawf	3	3	3	3	7	7	14
Shabwa	1	1	1	1	1	1	1
AL-Mahara	4	0	0	0	4	4	4
Aden	1	1	1	1	0	0	0
Amran	0	0	0	0	17	17	17
AL-Daleh	0	0	0	0	16	16	15
Sana'a City	0	0	0	0	2	2	2
Raimeh	0	0	0	0	0	0	19
Total	480	487	508	532	510	516	531

Table 6-11: Available dung from all ruminant stock

	Dung [1000 tons dry mass/year]						
Governorate/Year	1998	1999	2000	2001	2002	2003	2004
Hodeidah	44	44	44	46	53	53	65
Sana'a	52	55	56	58	35	35	19
Dhamar	31	32	32	33	36	37	34
Ibb	46	46	47	49	44	44	39
Taiz	34	34	35	36	38	39	39
Mareb	8	8	8	8	5	6	8
Hajiah	24	24	25	26	36	36	35
AL-Beida	11	11	11	12	10	10	10
Sadah	13	14	14	15	23	23	25
AL-Mahwit	10	8	8	9	13	13	10
Lahj	18	20	20	21	13	14	13
Abyan	11	11	11	12	11	11	17
Hadramout	10	10	18	19	19	20	27
AL-Jawf	5	5	5	5	9	9	18
Shabwa	6	6	6	7	13	13	16
AL-Mahara	6	4	4	5	7	7	10
Aden	2	2	2	2	1	1	1
Amran	0	0	0	0	18	18	16
AL-Daleh	0	0	0	0	11	11	10
Sana'a City	0	0	0	0	2	2	2
Raimeh	0	0	0	0	0	0	10
Total	329	335	348	364	396	401	425

6.5.2.2 Dung production from chicken and poultry

Chicken and poultry husbandry for egg and meat production has grown significantly (more than 8% per year) over the last six years with more than 8 percent annual growth rate. The total available dung volume from chicken and poultry in 2004 reached over 32,000 tons per year (Table 6-12), corresponding to a primary energy content of 10 tons of oil equivalent or 420 GJ.

Table 6-12: Dung production from egg and white meat production

	Dung [1000 tons dry mass/year]						
Governorate/Year	1998	1999	2000	2001	2002	2003	2004
Hen (layer and breeder)	12.3	12.4	17.4	17.6	17.9	18.3	18.6
Broiler	7.5	7.7	8.2	9.6	13.0	13.3	13.6
Total	19.8	20.1	25.5	27.1	30.9	31.6	32.2

6.5.3 Animal husbandry unit production level

6.5.3.1 Family farms

The typical composition of animals in family farms differs from region to region. The typical herd size per family farms is shown in Table 6-13.

In order to assess the available dung per family, the regional variation of the grade of herd confinement was considered to estimate the dung from various collection rates shown in Table 6-14.

Based on this information, the daily volume of dung per typical family farm and the energy available on an average family farm were calculated. The results are summarized in Table 6-15 and Table 6-16.

Table 6-13: Typical herd size of family farms per region and per type of animal

Region / heads per family	Cattle	Sheep	Goats	Donkey	Camel	Total
Coastal plains (Tihama)	1 – 2	10 – 15	10 – 15		0 – 1	25 – 30
Highlands (Sana'a, Al-Mahwit, Amran, …)	1	8	7	1		10 – 20
Middlelands (Ibb, Taiz, e.g.)	1 – 2	7 – 8	10	2		15 – 20
Dry areas (Shabwa, Hadramout)		15	3		2	10 – 20

Source: Eng. Jamil Al-Mamari, Directorate General of Animal Resources, MoAI

This analysis for an average production unit (family farm) shows that dung potential besides the promising total volumes on a per governorate level is not sufficient to satisfy the energy needs for cooking and lighting, in the case that fermenters are used to produce biogas. This means that biogas production on a family scale is currently not a viable solution for an average family.

Farm conditions that allow household biogas production are the following:

- Families with a herd size five times the average size
- Families that might be able to acquire dung from their neighbours
- Families with an extreme good dung collection rate and efficient energy management (low consumption).

Table 6-14: Grade of confinement and dung collection factor

Region	Cattle dung collection factor		Sheep, Goats, Donkey and Camel dung collection factor	
Coastal plains (Tihama)	Day: Outside grazing Night: confined in open area	0.4	Day: Outside grazing Night: confined in open area	0.4
Other regions	Day and night: confined in the families home ground floor	1	Day: Outside grazing Night: confined together with the cattle	0.5

Table 6-15: Daily volume of dung per typical family farm

Region / [kg/day]	Cattle	Sheep	Goats	Donkey	Camel	Total
Coastal plains (Tihama)	0.62	0.68	0.68		0.19	2.17
Highlands (Sana'a, Al-Mahwit, Amran, …)	1.04	0.54	0.47	0.36		2.42
Middlelands (Ibb, Taiz, e.g.)	1.56	0.34	0.68	0.73		3.30
Dry areas (Shabwa, Hadramout)		0.84	0.20		0.64	1.69

Table 6-16: Daily amount of biogas and energy available on an average family farm

Region	Biogas potential [m³/day]	Methane [m ³/day]	Primary energy content [1] kWh/day]	% of HH demand for cooking and lighting
Coastal plains (Tihama)	0.35	0.21	2.07	12%
Highlands (Sana'a, Al-Mahwit, Amran, …)	0.42	0.25	2.52	14%
Middlelands (Ibb, Taiz, e.g.)	0.60	0.36	3.60	20%
Dry areas (Shabwa, Hadramout)	0.27	0.16	1.62	9%

[1] based on the lower heating value of methane

6.5.3.2 Large-scale animal husbandry

Besides family farming according to to Eng. Jamil Al-Mamari, Directorate General of Animal Resources, MoAI, some large cattle herds can be found in the following regions:

- Hodeidah Governorate (around Bajil and Azerah)
- Ibb and Taiz Governorate
- Al-Baydah

In total there are about 7-8 dairy farms with each 400 – 500 heads of Friesian cows for milk production.

In Hodeidah, a cooperative owns an even larger herd with about 2500 heads. Several smaller farms in the same region have herds with around 50 – 100 heads each farm. Using collection factors presented earlier and assuming slightly higher average live weight than in the previous analysis, the gas volumes and corresponding power and energy yield assuming combustion in a typical piston spark ignition engine generator set were estimated. These are summarized in Table 6-17.

For larger herds (typically 400 heads and more) the analysis shows a biogas potential that might be explored for power generation. For smaller herds the biogas potential might be utilized to satisfy on farm heating needs e.g. in milk processing or lighting (gas lamps). An estimation of the total potential for electricity generation is given Table 6-18.

Table 6-17: Average potential for biogas production in typical shed

Size of farm	Life weight	Average dung/day	Biogas	Methane	Electricity	Electricity	Power
	[kg/head]	[kg/d]	[m³/d]	[m³/d]	[kWh/d]	[GJ/y]	[kW_24h]
2500 Friesian	500	10,000	2,031	1,220	3660	4,809	153
400 Friesian	500	1,600	325	195	585.6	769	24
75 local race	300	180	36.6	22.0	65.88	87	3

Table 6-18: Large scale farm biogas production potential

Size of farm	Electricity [GJ/y]	Number	Total Electricity [GJ/y]
2500 Friesian	4,809	1	4,809
400 Friesian	769	7	5,386
Total			**10,196**

Besides cattle, poultry is also raised or kept in larger concentration. Around 3,500 poultry sheds exist currently in Yemen. Most of them can be found around the larger urban centres. The average number of poultry per shed varies with the purpose of their creation: breeder, broiler or layer. The average number heads in poultry sheds is given in Table 6-19.

Based on these data, the biogas and electricity generation potential can be identified for a shed of the average size. This is given in Table 6-20 The said table shows a power generation potential which is at the lower technical limit that could be used in spark ignited piston engines. However the biogas could be used on farm for illumination to increase feeding time and productivity.

Only for larger production units consisting of at least 5 to 10 sheds, the biogas based power production becomes technically feasible.

Table 6-19: Average number of heads in poultry sheds

Class of poultry	Average number of heads per shed	Comments
Breeder	6 – 6.000	
Layer	7 -8.000	
Broiler	10 – 13.000	Generally slaughtered with 50 days

Source: Eng. Jamil Al-Mamari, Directorate General of Animal Resources, MoAI

Table 6-20: Average potential for biogas production in typical shed

Class of poultry	average dung/day	Biogas	Methane	Electricity	Electricity	Power
	[kg/d]	[m³/d]	[m³/d]	[kWh/d]	[GJ/y]	[kW_24h]
Breeder	113.2	35.41	21.25	63.75	84	3
Layer	121.29	37.94	22.76	68.28	90	3
Broiler	46.64	14.59	8.75	26.25	34	1

6.6 Forestry Biomass Resources

6.6.1 Fuelwood and charcoal

Forest based biomass has been traditionally used to satisfy the basic energy needs for cooking and heating in Yemen. In the 1970s and 80s, Yemen's standing stock of wood had been dramatically reduced mainly due to firewood consumption. During the last decade traditional fuels have been replaced to a large extend by LPG. LPG has been made available in small cylinders in most of the Governorates at accessible prices. However in remote rural areas, fuelwood and charcoal are still important cooking fuels, as it is sold at more competitive prices. Besides, charcoal is also consumed in urban areas in small quantities for smoking Shisha.

Figure 6-9 and Figure 6-10 show a typical wood market on the road from Al-Mocha to Taiz. Thin branches are sold as firewood and larger branches are used for charcoal production. But in general, the diameter of branches and stems reveals that small and young trees are used, which indicate that the standing stock of trees has not yet recovered from the wood resource gathering pressure.

Figure 6-9: Wood market close to Taiz

Figure 6-10: Earth kilns close to Taiz

6.6.2 Available data

In order to assess the woody biomass resources data from the following reports has been taken into account:

1. FAO, Global Forest Resources Assessment 2005, Country Report Yemen, Rome 2005
2. National symposium on Desertification Report (work paper) 1996

All data available to the consultant was on a national level, therefore no disaggregation to governorate level was possible. All available base data is for 1993 and elaborated in the “National land and water conservation wood land resources mapping project” based on Landsat imagery, field work and air photography in 1993.

6.6.3 Forest types and forest cover, stock and productivity

Despite being the green tip of the Arab Peninsula, Yemen's tree and forest cover is relatively low. Forests occupy only 1% of all land. In total less then 5% of all land area show any tree cover.

The data presented in Table 6-21 dates back to 1993 and elaborated in the "National land and water conservation wood land resources mapping project". The 2005 data is taken from the Country Report Yemen which is part of the FAO Global Forest Resources Assessment 2005. It is an Extrapolation to the 2005 situation and based on expert estimations. According to Mohamed Hassan Moqbil, Head of the Natural Forest Department (Government of Yemen), who prepared the FAO report one can assume, that reductions in stock and area in the coastal plains and escarpment are counterbalanced by regeneration of the mountain forests, thus yielding to an unchanged overall picture in 2005.

Table 6-21: Forest and tree cover in Yemen

	1993	2005	
Categories	[km²]	[km²]	Share of total land
Forest	5,489.53	5,489.53	1.0%
Other wooded land	14,060.25	14,060.25	2.7%
Agro-forestry and Date Palms	4,229.89	4,229.89	0.8%
Other land with tree cover	421.25	421.25	0.1%
Total land with trees	24,200.92	24,200.92	4.6%
Total Land of Yemen	527.970,00	527.970,00	100,0%

All "forests and other wooded land" are multiple purpose and designated to any combination of: production of goods, protection of soil and water, conservation of biodiversity and provision of social services and where none of these alone can be considered as being significantly more important than the others. Some areas are designated for Conservation of biodiversity, but are still used by communities for other purposes.

There are no natural forests and no forest plantations in Yemen. All forest and other wooded land is either modified natural consisting of naturally regenerated native species where there are clearly visible indications of human activities or semi-natural consisting of native species, established through planting, seeding or assisted natural regeneration.

Table 6-22 shows that almost three-fourths of all land with tree cover is located in the Western Mountains and the Escarpment. The small areas with Juniper stands, which are tertiary relicts that have adapted to the harsh conditions of the dry Yemeni mountains also are found in these area. The Mahra Woodlands are located on the boarder with Oman, receiving almost all precipitation in form of mist.

Table 6-22: Regional distribution of forests and land with trees in Yemen

National class	Forest and Woodland [km²]	Agro-forestry and Date Palms [km²]	Other land with trees [km²]	Total land with trees [km²]	Share of total land with trees
Coastal Plains	1.561,66	51,81		1.613,47	6,7%
Escarpment and W. Mountains	14.050,08	3.810,64		17.860,72	73,8%
Central Highlands and Wadis	3.748,63	367,44		4.116,07	17,0%
Mahra Woodland	168,09			168,09	0,7%
Juniper	21,32			21,32	0,1%
Other			421,25	421,25	1,7%
Total	19.549,78	4.229,89	421,25	24.200,92	100,0%

6.6.4 Stock of wood and biomass

The stock of wood in Yemen is estimated to be 16,8 million cubic meters. This is in average less than 7 m³/ha of forests or wooded land illustrating the low density of the tree cover (Table 6-23). There is no stock of commercial value, i.e. value for timber production.

Taking into account all branches, twigs and leaves etc. the volume of biomass above ground adds up to around 25 million tons dry weight. In average this corresponds to about 10.5 tons of biomass per hectare (Table 6-24).

Table 6-23: Growing stock in Yemen's forests and wooded lands

Categories / Volume (million cubic meters over bark)	Forest + Other wooded land		
	1990	2000	2005
Growing stock	16,8	16,8	16,8
Commercial stock	–	–	–

Table 6-24: Biomass volume in Yemen's forests and wooded lands

Categories / Biomass (million metric tonnes oven-dry weight)	Forests + Other wooded land		
	1990	2000	2005
Above-ground biomass [1]	25,5	25,5	25,5
Below-ground biomass [2]	11,0	11,0	11,0
Dead wood biomass [3]	5,1	5,1	5,1
TOTAL	41,6	41,6	41,6

[1] All living biomass above the soil including stem, stump, branches, bark, seeds, and foliage

[2] All living biomass of live roots. Fine roots of less than 2mm diameter are excluded because these often cannot be distinguished empirically from soil organic matter or litter

[3] All non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter or any other diameter used by the country

6.6.5 Forest Potential as Source of Energy

In order to assess the sustainable production of wood in Yemen's forests and wooded lands, the detailed breakdown of forest, wooded land and land with tree cover into classes according to the national classification has been used (Table 6-25).

Table 6-25: Total wood production in Yemen

National Classes	Area	Forest	Other wooded land	Other land with tree cover	Mean annual increment	total wood production
unit	km²	km²	km²	km²	m³/ha	1000 m³
P1 - Mangrove woodland	9,27	9,27			5,00	4,64
P2 - Cultivated date palm	51,81			51,81		
P3 - Hyphaene woodland	50,16	50,16			3,00	15,05
P4 - Salvadora thicket	107,96		107,96		3,00	32,39
P5 - Tihama Acacia woodland	175,61	105,37	70,24		3,00	52,68
P6 - Tihama Acacia woodland and agriculture	273,96	136,98			1,50	20,55
P7 - Plains agriculture	6.733,70					
P8 - Acacia-Commiphora woodland on gravel plains	1.081,68	540,84	540,84		3,00	324,50
P9 - Range/bare land	8.872,28					
E1. Acacia- Commiphora woodland /shrubland	12.430,15	2.486,03	9.944,12		3,00	3.729,05
E1a. Acacia- Commiphora woodland /shrubland	322,65	64,53	258,12		3,00	96,80

E2. Terraced Agriculture with Acacia shrubland	2.481,37		1.240,69		1,50	186,10
E3. Riverine Forest	3,00	3,00			3,00	0,90
E4 - Riverine agriculture with forest trees	61,46					
E5 - Agriculture with trees on field margins	3.749,18					
E6 - Agriculture predominantly terraced	4.567,79					
E7. Riverine Acacia woodland.	53,59	53,59			3,00	16,08
E8 - Agriculture and bare lands	5.837,08					
E9 - Range/bare land	13.237,76					
C1. Acacia open woodland.	3.321,16	1.992,70	1.328,46		3,00	996,35
C3 - Date palm agriculture	345,26			345,26	1,50	51,79
C4. Tamarix woodland	427,47		427,47		3,00	128,24
C5 - Zizyphus orchards	24,18			24,18	3,00	7,25
C6 - Agriculture	3.343,05					
C7 - Range/bare land	81.564,01					
J - Juniper woodland remnant	21,32	21,32			3,00	6,40
M1. Anogeissus woodland.	56,18		56,18		3,00	16,85
M2. Anogeissus Parkland.	6,78		6,78		3,00	2,03
M3. Anogeissus woodland with clearings	6,20		3,10		3,00	0,93
M4. Commiphora -Acacia shrubland	50,53		50,53		3,00	15,16
M5. Commiphora -Acacia woodland	51,50	25,75	25,75		3,00	15,45
M6 - Range/bare land	1.196,87					
Other land	529,48					
Total	151.044,45	5.489,53	14.060,25	421,25		5.719,18

Assuming a Mean Annual Increment varies between 1.5 and 3 m³/ha for various classes of forest or tree cover and 5 m³/ha for mangrove, one obtains a total sustainable production of wood of around 5.7 million cubic meters per year.

To estimate the amount of wood available for energy purposes one would need data on the demand of wood for other purposes. There is no data available for industrial wood removal and wood removal for construction. However wood is used for this purpose at least in the in traditional construction.

The World Bank in 1988 estimated fuel wood consumption in Yemen to be about 4.7 million m³ per year. According to FAO, this has decreased in last decade, as a result of fuel substitution with LPG in several governorates. In some districts wood fuel still continues to the predominant household fuel. This is true especially in the remote areas with difficult access, where transport adds an additional cost to the LPG sold, thus making it non competitive with the traditional wood fuel.

One can state that wood resources are extremely scarce in Yemen. As there is neither forest plantation nor timber production in the country, no residuals from timber production are available. Densities of forests or tree cover are very low as well as the mean annual increment.

Modern biomass energy for power supply which is the focus of this study would require even on a very small scale wood resources which are enormous compared to the productivity and density of Yemeni forests.

Table 6-26 shows two examples for village biomass energy systems. The first might supply around 10 to 15 families, the second around 30 to 70 families. The smaller system requires over 40 hectares of forests for a sustainable fuel supply. The latter requires almost 600 hectares of forests or woodland to sustain the system.

Table 6-26: Fuel demand of village biomass energy systems

Power [kW]	Efficiency of energy conversion	Fuel demand [MWh]	Fuel demand [ton of dry wood]	Forest area required [ha] [1]
6	20% [2]	262.8	59	44
40	10%[3]	3504	789	585

[1] An average sustainable production of 2.25 m³/ha and year is assumed

[2] Compact biomass Organic Rankine Cycle system

[3] Small boiler-steam engine system

6.7 Municipal Waste

6.7.1 Waste Situation in Yemen

Besides the biomass potential from agricultural residues, there also exists a potential from municipal solid waste to be exploited for energy production in Yemen.

The per-capita waste generation in Yemen is amongst the lowest in the Arab region, with a figure of 165 Kg per capita and year. The municipal solid waste is partially collected and dumped in landfills, as shown in Table 6-27.

Table 6-27: Quantities of solid waste collected in Yemen, 2000

Governorate*	No. of official dumps	Solid wastes in Governorate centers [t].		
		2004	2003	2002
Abyan	1	11,520	11,000	11,000
Aden	1	206,564	120,268	250,000
Al - Jawf	1	720	2,500	2,500
Al-Beida	1	66,840	42,820	25,000
Al-Daleh	1	14,929	5,510	1,500
Al-Hodeidah	1	139,439	105,935	81,518
Al-Mahrah	1	16,616	2,160	4,850
Al-Mahweet	1	12,214	6,977	6,043
Amran	Combined with Sana'a	9,228	5,782	50,400
Dhamar	1	24,915	17,870	18,592
Hadramout	2	28,027	59,263	120,500
Hajjah	1	7,800	10,361	21,310
Ibb	1	39,921	47,165	28,910
Laheg	Combined with Aden	4,800	2,924	10,200
Mareb	1	12,720	8,370	28,000
Sa'adah	1	14,300	20,000	20,000
Sana'a	1	40,070	43,780	65,000
Sana'a City	Combined with Sana'a	361,585	453,600	453,600
Shabwah	1	10,013	14,510	6,050
Taiz	1	144,261	123,900	105,000
Total	**18**	**1,166,482**	**1,104,695**	**1,309,973**
* No Data available for the new governorate Raymah				

Source: Ministry of Works and Road (Gen. Director of Environmental Hygiene)

To evaluate the energy potential, detailed information about the waste composition is needed. Since this information is not available, a composition was assumed as a general figure for the estimation. This is shown in Table 6-28.

Table 6-28: Typical waste composition

Organic matter	55 percent
Paper	14 percent
Plastic	13 percent
Glass	1.5 percent
Metal	2 percent
Rest (inert)	14.5 percent

Inadequate municipal solid waste management is a serious problem in Yemeni cities as well as in small towns and villages. Waste collection is especially poor in the low-income neighbourhoods, where most of the waste is dumped into wadis, streets, and open dumps. In many cases, accumulated refuse and the stagnant water resulting from the clogging of drainage systems, serve as breeding grounds for rats and insects, contributing to both disease and nuisance.

6.7.2 Waste Treatment Options

The primary aim of waste management is its safe disposal in order to avoid health risks for the population and damage to the environment. The generation of energy is an additional aspect that can be taken into consideration.

In principle, there are two possibilities to make use of the calorific value contained in municipal waste:

- Incineration in a waste incineration plant
- Combustion of the landfill gas produced in a landfill by anaerobic digestion.

For both technologies, the main aim is to reduce the amount of harmful substances, while energy production is only a secondary effect.

As described above, incineration of municipal waste is not regarded as suitable technology for energy generation for Yemen. The utilisation of landfill gas is being assessed.

Landfill gas is generated naturally in every dump and landfill by anaerobic digestion. The amount of gas produced depends on the extent of the anaerobic zone and other factors such as moisture content and temperature. Usually, landfill gas is collected and used for energy generation only at large scale landfills that have been prepared for that aim in advance.

6.7.3 Energetic Potential

The main factors that typically influence the amount and composition of landfill gas are:

- Yearly input
- Age of landfill
- Waste composition
- Density of waste (height of landfill)

- Moisture content and distribution
- Temperature
- Presence of toxic agents and chemical inhibitors

Since this information is not available, the estimation is made based on the waste input flows, the waste composition and further assumptions shown in Table 6-29.

Table 6-29: Landfill gas production and use

Extension of Anaerobic Zone [%]	80
Methane generation per ton of org. material [m^3]	150
Gas collection rate [%]	40
Efficiency of electricity generation [%]	22

On the basis of these assumptions, a total physical potential in the range of 1,270 TJ/y of energetic value of the landfill gas results. This is a merely theoretical value, as it implies both the landfilling of the total amount of waste under conditions suited for anaerobic digestion as well an installation of landfill gas capture and combustion stations at all landfills.

The collection and usage of landfill gas is viable only at very large landfills. For the estimation of the technical potential, the following landfills will be taken into account:

- Aden
- Al-Hodeidah
- Sana'a + Sana'a City
- Taiz

Further, regarding the technical potential, the status of the existing landfills has to be considered. Although detailed in information is not available, for the status of the above listed landfills the following assumptions can be made that could lead to problems or a considerable reduction of the potential:

- The waste in most of the landfills is not compacted. Therefore the aerobic zone dominates, while only in the anaerobic zone methane is produced.
- The waste is very dry. That inhibits the methane generating micro organisms. Usually as a measure of moisture control the leachate is collected and re-circulated, which only is possible if the landfill ground has been design for leachate collection.

Accordingly, for the existing landfills, the usage of landfill gas does not seem to be an interesting option. From the environmental point of view the recovery of the gas is of low importance as well, since from well aerated and dry only low amounts are emitted.

Nevertheless, assuming the construction of new landfill sites, for the above listed governorate centres the potential was estimated. This is shown in Table 6-30.

Table 6-30: Technical potential for energy production from landfill gas

Governorate Centre	Waste [t/y]	Landfill gas [m^3/y]	Methane [m^3/y]	Energetic Value [TJ/y]	Electricity [TJ/y]	Max. installed Capacity [MW]
Aden	206,564	11,402,333	6,841,400	225	50	1.74
Al-Hodeidah	139,439	7,697,033	4,618,220	152	33	1.18
Sana'a + Sana'a City	401,655	22,171,356	13,302,814	438	96	3.39
Taiz	144,261	7,963,207	4,777,924	157	35	1.22
Total	891,919	49,233,929	29,540,357	972	214	7.53

For a detailed assessment of the technical potential of a specific landfill, after a first theoretical data evaluation, measurement of the current gas production is necessary. The installed capacities are maximum capacities, which in many cases are not installed at once – especially in landfills that are still in use for waste disposal.

6.8 Waste Water

6.8.1 Water Situation in Yemen

Yemen is a water-scarce country, and natural fresh water availability is among the lowest of the world. The annual renewable water resources are declining due to overexploitation, caused mainly by the rapid expansion of groundwater use for agricultural irrigation since the 1980s. Especially in the Sana'a region, the situation is critical.

Public health and clean water supplies are also at risk due to the poor provision of sewage collection and treatment systems. Sewerage systems exist in all major agglomerations, but the connection rate is low (overall connection rate was 6.2% in 2004), and quality of the treated water relatively poor. Further, both treated and untreated water is used for agricultural irrigation, causing severe health risks to the population.

Although significant improvements to public health have been achieved in recent years through the construction of sewerage systems and wastewater treatment plants in some towns, Yemen still has rapidly declining water resources and a high incidence of water-borne diseases.

6.8.2 Waste Water System

In Yemen, the larger agglomerations and some smaller cities dispose of waste water treatment facilities. However, the rapid rate of expansion of many towns has resulted in overloaded and inadequate collection and treatment systems, resulting in the discharge of raw and partially treated sewage.

In recent years, the number of sanitation projects has grown rapidly, mostly financed by International funds. There are now more than 20 waste water treatment plants

(WWTPs) in Yemen, either operating, under construction or at the design stage. The majority of WWTPs are waste water stabilisation pond systems, which is the most appropriate treatment for the local conditions, and if operated correctly, should produce effluent suitable for unrestricted reuse.

The total actual flow is about 200,000 cubic metres per day, or 73 million cubic metres per year (Table 6-31).

Table 6-31: Waste water treatment plants in Yemen

Station	**Governorate**	**Capacity (m^3/d)**	**Type of Treatment**	**Status / commissioning Date**
Aden (Ash Shaab)	Aden	11,000	3 stage stab. ponds	1970s, extended 1989
Aden (Ash Shaab, ext.)	Aden	30,000	3 stage stab. ponds	Design stage
Aden (Al Arish)	Aden	70,000	3 stage stab. ponds	2002
Amran	Amran	1,480	3 stage stab. ponds	2002
Bait El Faquih	Al-Hodeidah	2,544	3 stage stab. ponds	Under construction
Bajil	Al-Hodeidah	4,151	3 stage stab. ponds	Under construction
Dhamar	Dhamar	11,000	3 stage stab. ponds	1992
Haijah (Main)	Haijah	2,428	Imhoff t. / Trickling filter	1998
Haijah (LS6)	Haijah	724	Imhoff tank	1998
Haijah (LS8)	Haijah	253	Imhoff tank	1998
Hodeidah (existing)	Al-Hodeidah	12,000	3 stage stab. ponds	1983
Hodeidah (ext.)	Al-Hodeidah	51,500	3 stage stab. ponds	Under construction
Ibb (existing)	Ibb	5,200	Activated sludge	1991
Ibb (extension)	Ibb	10,000	Imhoff tank	Under construction
Mukalla	Hadramout	14,000	Stabilisation ponds	Under construction
Al Quaida	Taizz	2,650	Imhoff / Trickling filter	Design stage
Rada	Al-Beida	1,880	2 stage stab. ponds	1996
Sana'a	Sana'a	50,000	Activated sludge	2000
Seiyun	Hadramout	9,300	Stabilisation ponds	Design stage
Taizz	Taizz	17,500	3 stage stab. ponds	1982
Tarim	Hadramout	8,000	Stabilisation ponds	Design stage
Yarim	Ibb	1,771	3 stage stab. ponds	2003
Zabid	Al-Hodeidah	1,146	Imhoff tank / stab. pond	Under construction

Since major heavy industries are absent from all catchments, heavy metal concentrations in effluent and sludge are relatively low and not the main problem in Yemen (as they are in many other countries). The major challenge is ensuring that the microbiological quality of effluent and sludge is suitable for the reuse conditions, due to the high prevalence of enteric diseases in the population. Sludge and water from ponds and Imhoff tanks have undergone digestion, but pathogen concentration is not sufficiently low to be safe for manual handling of the sludge.

6.8.3 Waste Water Utilisation

Water reuse in agriculture is common throughout the Middle East and North Africa. Two ways of water reuse for irrigation are distinguished:

- Planned/controlled: through specifically designed projects to treat, store, convey and distribute treated wastewater for irrigation. Examples of planned reuse can be found in Egypt and Tunisia [Waste Water Management Tunisia].
- Unplanned / uncontrolled: Often after discharge into open watercourses. Can be the case for waste water that is treated to some extent, and untreated waste water.

The latter is also the case if waste water treatment plants exist but are not operated and maintained adequately, making wastewater unsuitable for unrestricted irrigation.

Controlled irrigation is practised by the Yemeni Ministry of Agriculture and Irrigation for green belt building or desertification control along the coastal plains. Non-controlled irrigation is commonly practised by many farmers both with treated and untreated waste water, either by diverting new perennial wadi flow or by blocking sewer mains to flood irrigate their land. The water is used in the highlands and wadis to grow corn, and forage crops as well in some areas (Ta'izz area), and to grow vegetable and fruit crops (Sana'a area). Farmers are working with this water without any form of training and usually unconcerned about the health risks to them, their families or consumers of the crops.

The low quality of the treated effluent and the use of untreated waste water have created a number of problems:

- Odours and insects at some treatment stations
- Public health hazards and skin diseases among farmers
- Soil salinity problems
- Plant diseases in crops irrigated with treated waste-water
- Animal diseases due to direct contact with the treated waste-water.

Accordingly, an extension and improvement of the waste water treatment system is of prior importance in Yemen. An additional use of the sewage sludge for energy generation is desirable, but only of subordinate importance.

6.8.4 Sewage Sludge Utilisation

Detailed data on the amount and current use of sewage sludge for the above listed sewage plants was not available. However, a great share of the sludge produced in Yemen is air-dried, either in situ in anaerobic ponds or on drying beds, and used as agricultural fertiliser. Arrangements between the WWTP and farmers are ad hoc, without control or recording of user and fertilised land.

On the basis of the figures stated the table "Number of Subscribers and Beneficiaries of Sanitary Sewage Service" in the "Statistical Year Book 2004 for the Republic of

Yemen", and assuming a yearly production of 15 kg dry mass per connected inhabitant per year (dm/(Inh*d)), a total sludge production in the range of 21,000 tdm/y to 29,000 tdm/y is [Lebanon, EU]). For the above listed WWTPs, it is estimated that the total sludge production in Yemen is expected to exceed 40,000 tds/y within a ten years.

Assuming an annual rate of application rate to land is 4 tds/ha, about 10,000 ha (1% of total cultivatable area of Yemen) would be required annually to use this quantity of sludge. As described above, the main concern of the use of sludge as a fertiliser – the accumulation of heavy metals in soil after long-time use - is not expected to be a critical issue in Yemen due to the limited quantity of industrial effluents discharged to the sewer system.

Accordingly, the main and priority use of sewage sludge in Yemen is the application as agricultural fertiliser, both at present and in the future.

For the small stabilisation pond WWTPs, sufficient farmers in the locality are likely to take the sludge directly. While a melioration of the final treatment of the sludge is suggested in order to minimise the risk for the labourers and farmers, a production of biogas and its energetic use are not viable.

For the major sludge production centres with an waste water capacity > 30,000 m^3 an anaerobic digestion with biogas production is a viable option. A biogas production for the following site is assessed:

- Sana'a,
- Aden
- Hodeidah

The digested sludge has the same suitability as fertiliser as the non-digested sludge. It could be dried afterwards in the same way as the raw sludge. Additionally, the digested sludge is less harmful due to lower biological activity. In both cases, logistic issues have to be resolved, especially for Aden and Hodeidah, being located on the coast with only limited agricultural land nearby.

6.8.5 Potential for Biogas and Energetic Output

In order to calculate the amount of biogas that can be produced from sewage sludge, detailed data about its composition are required. As mentioned above, neither the amounts of sludge produced nor the sludge composition was available.

For this reason, an estimation based on typical values is made in the following, based on the assumption specified in Table 6-32.

Table 6-32: Sewage sludge utilization

Amount of sludge d.m. per inhabitant [kds/y]	20
Content of organic dry matter [%]	65
Sewage gas production per kg of o.d.m. [m^3]	0.55
Methane content of sewage gas [%]	60
Efficiency of electricity generation [%]	22

Based on these assumptions, a theoretical physical potential in the range of 200 TJ/a is estimated (Table 6-33).

Table 6-33:Total Sewage Sludge Potential

Station	Governorate	Capacity [m^3/d]	Persons connected	Sewage Sludge [t/y]	Methane [m3]	Energetic Value [TJ/y]
All Stations		318,527	1,395,044	27,901	5,984,739	197

For the three major sewage sludge production centres the results shown in Table 6-34 are obtained.

Table 6-34: Sewage Sludge Technical Potential

Station	Gover-norate	Capacity [m^3/d]	Persons con-nected	Sewage Sludge [t/y]	Methane [m3]	Energetic Value [TJ/y]	Electricity Generation [TJ/y]	Max. installed Capacity [MW]
Aden (Ash Shaab)	Aden	11,000						
Aden (Ash Shaab, ext.)	Aden	30,000						
Aden (Al Arish)	Aden	70,000						
Aden TOTAL		111,000	485,100	9,702	2,081,079	68	15	0.53
Hodeidah (existing)	Hodeidah	12,000						
Hodeidah (extenstion)	Hodeidah	51,500						
Hodeidah TOTAL		63,500	200,424	4,008	859,819	28	6	0.22
Sana'a	Sana'a	50,000	263,977	5,280	1,132,461	37	8	0.29
Total		224,500	949,501	18,990	4,073,359	134	29	1.04

6.8.6 Decentralised Waste Water Usage

Another option for the use of human excrements for energy generation in areas without waste water collecting system is to feed them directly into a biogas plant. At the village level, the human excrements can be mixed with other organic residues like kitchen waste and cow dung as feedstock and digested in small scale fermenters.

In specific cases, a bigger biogas plant in common could serve and be supplied by a group of several hundreds of people. This might be an option for big schools, hospitals, prisons, barracks or other places where lots of people gather. There is usually a hygienic problem with the disposal of the excrements if many people are living in one small area. The main aim of such a biogas plant is to solve hygienic problems. On the other hand, the production of biogas can substitute fuel wood for cooking.

100 persons are producing enough feedstock for up to 2 - 2,5 m³/d methane (equals up to 4 m³/d biogas). Since methane has a calorific value of 10 kWh/m³, this corresponds 32 GJ/a.

6.9 Summary

The Republic of Yemen is an agricultural country with vast agricultural resources. Agriculture was and still is the main stay of the economy. It contributes nearly 18% to the gross national product (GNP), provides employment to over 16% of the country's workforce and livelihood for all the rural residents - who constitute nearly 76% of the total population.

The total arable area is estimated to be about 9.5% of the total land area of the country and thus very limited. The limiting factor is rainfall and scarce water resources for irrigation. So, the cropped area varies from one year to another depending on the amount of precipitation. On average, it is about 1.1 million hectares (ha) but in year of ample and well-distributed rainfall, it could reach 3.5 million ha. It must be noted that nearly half the area of the country is considered desert and range land subjected to continuous deterioration.

Land and water resources are already being used intensively for growing foods and to generate cash income. Therefore the biomass potential is limited to residual products from agriculture, animal husbandry, forestry as well as food processing industry (Table 6-35). Special energy crops for bio energy or bio fuels have not been considered as a viable option since they cannot compete economically and subsidising is not recommended as food security is primary.

Table 6-35: Biomass technical potential

Resource	Physical Potential	Technical Potential
Energy crops	–	–
Agricultural crop residues	–	–
Animal husbandry residues		0.36 MW
Forestry biomass residues	–	–
Municipal waste (landfill gas)	1,270 TJ/y	7.53 MW
Waste water (sewage sludge)	200 TJ/y (+ decentralised utilisation)	1.04 MW (+ decentralised utilisation)

7 Renewable Energy Development Options

7.1 Grid-based Renewable Energy Options

Wind, solar and geothermal energies are the most important renewable energy resources in Yemen that can sustain commercial scale grid-based power generation. Limited amount of biogas from municipal solid waste (MSW) could also be potentially developed commercially. Despite the huge renewable energy potential in the country, power projects that could be aggressively but pragmatically developed in the next 10 years, given favourable economic, political and institutional factors, are summarized in Table 7-1.

This pipeline of projects could be implemented through private sector partnerships, particularly through independent power production. One of the long-term objectives of the Power Sector Strategy is to open up the sector for greater private sector participation. As discussed in Task 2 of this Study, the Medium Term Power Sector Development Strategy Note issued in 2006, due to the government's failure to negotiate an IPP contract since the 1990s, stipulates the GOY's intention to pursue conventional financing for the Power Sector Medium Term Investment Plan (ending in 2010), and explores for alternative models of public private partnerships other than IPP.

Table 7-1: Renewable Energy Power Development, 2010-2020

Year	Wind (MW)	Geothermal (MW)	Solar (MW)	Landfill Gas (MW)	Total (MW)
2010	10 [1] (Mokha/Hodeidah)			3 [1] (Sana'a)	**13**
2011					
2012	100 (Aden/Mokha)		10 [1]	3 (Aden, Taiz, Hodeidah)	**113**
2013					
2014	100 (Aden/Mokha)	5 [1] (Dhamar)			**105**
2015			50		**50**
2016	50 (Mokha or Aden)				**50**
2017					
2018					
2019					
2020	80 (4 sites in Highlands)	50 (Dhamar)	50		**180**
Total	**340**	**55**	**110**	**6**	**511**

Note: [1] could be developed as pilot projects with public sector financing

These projects are however proposed for the period 2010-2020, and as argued in Task 2 of this Study, the current Power Sector Reforms could have been implemented with positive results while the international investment climate on IPPs during this period could have been improved. Also, given the magnitude of required investments as well as the expertise needed in operating these proposed power plants, the GOY could not completely rely on its financial resources but needs the private sector to fill in these requirements. The first few projects could however be carried out in the country as pilot projects funded by the public sector. These projects are briefly outlined in the following sections.

7.1.1 5 MW Wind Power Project

As presented earlier, regions with high wind regimes (high capacity factor) range from southwest to southern coastal plains of the country (from Taiz to Lahej, Aden and some part of Abyan governorate) and some specific sites in Yemen's highlands. The government could initiate wind power development in these regions, particularly in sites where the national grid is easily accessible.

The study proposes to start with wind power development in two sites where the current wind measurement campaign is implemented, Al Mokha and Al-Hodeidah, and with capacities of 5 MW in each site. Al Mokha and Aden, regions with highest potential, could be further developed with batches of 50 MW wind farms from 2012 until 2016.

Yemen's wind atlas also shows high potential in some areas close to major cities and the national grid in the Highlands. Four areas could be identified and assessed through further site investigations and wind measurements. Development of these areas could start in 2020, and with possible terrain constraints, a 20 MW wind farm could be developed in each site.

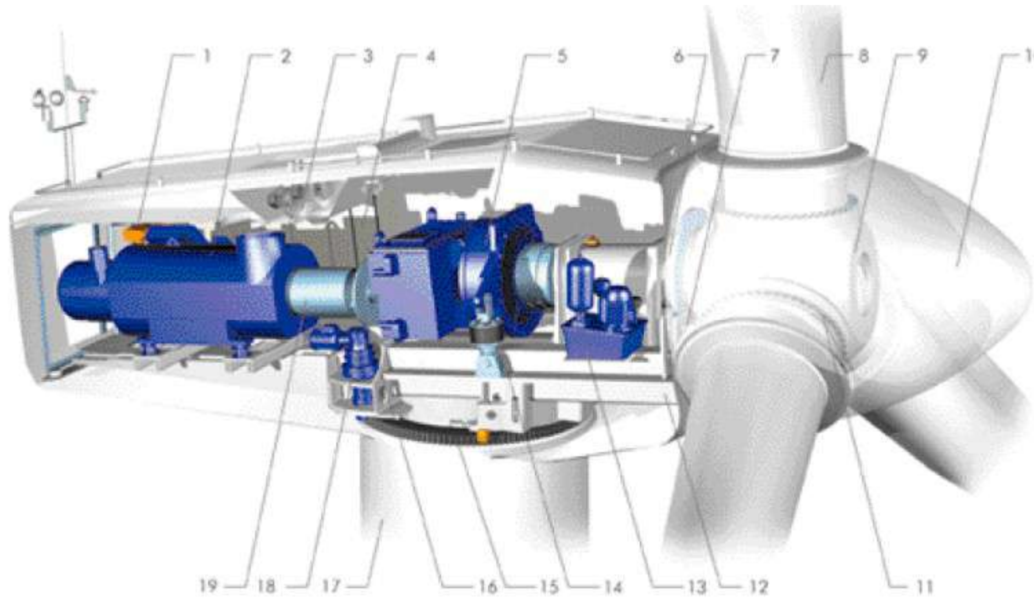
7.1.1.1 Technology

On-shore wind energy technologies available in the market are in units from few hundred kilowatts to around 3 Megawatts. Major components of the standard commercial wind turbine consist of the following: i) rotor blades, ii) generator, iii) aerodynamic power regulation, iv) yaw mechanism, and v) tower.

The rotors of modern wind turbines generally consist of three blades, with their speed and power controlled by either stall or pitch regulation. Stall regulation involves controlling the mechanical rotation of the blades, pitch regulation (now more commonly used) involves changing the angle of the blades themselves.

Energy captured by the steadily rotating blades is transferred to an electrical generator via a gearbox and drive train. Alternatively, the generator can be coupled directly to the rotor in a "direct drive" arrangement. Turbines able to operate at varying speeds are increasingly common, a characteristic which improves compatibility with the electricity grid.

The gearbox, generator and other control equipment are housed within a protective nacelle. Tubular towers supporting the nacelle and rotor are usually made of steel, and taper from their base to the top. The entire nacelle and rotor are designed to move round, or "yaw", in order to face the prevailing wind. A more detailed description of a modern wind turbine is shown in Figure 7-1.



1. service crane
2. generator
3. cooling system
4. VMP-top controller with converter
5. gearbox
6. main shaft
7. rotor lock system
8. blade
9. blade hub
10. Spinner
11. blade bearing
12. machine foundation
13. hydraulic unit
14. gear torque arm
15. yaw ring
16. brake
17. tower
18. yaw gear
19. composite disc coupling

Figure 7-1: Wind turbine components

Wind turbines are group into classes according to their ability to withstand wind conditions. These classes are characterized by the 10-minute average value of the extreme wind speed with a transgression probability once every 50 years and turbulence intensity criteria at a wind speed of 15 m/s at hub height.

In a separate study, the Wind Resource Assessment Study, an analysis of an optimal wind turbine class was undertaken taken into account the wind conditions. The Study recommended a class II wind energy converter unit with an installed capacity of 850 kW as the optimal turbine size.

7.1.1.2 Costs

A total of 6 turbines will be required by the project if using a class II wind energy converter with an installed capacity of 850 kW. A capacity factor of 30 percent is assumed in the study. The wind resource assessment study shows that wind regimes in this region are very good which could attain more than 2500 full load-hours operation in a year. The total annual generation amounts to 12.1 GWh. The design parameters are shown in Table 7-2.

Capital and O&M costs assumptions are summarized in Table 7-3 and Table 7-4. These figures are taken from the World Bank sponsored study on *Technical and Economic Assessment: Off-grid, On-grid and Grid Electrification Technologies*. These figures are based on international data hence more specific conditions in Yemen are not being considered. At present, this information is sufficient since the main objective of this analysis is to estimate benchmark figures for different renewable energy technologies in the country.

A 5 MW wind farm in Al Mokha requires a minimum investment of US$ 7.14 million in 2004 prices. A simple spreadsheet model is used in estimating the unit generating cost of the project. A discount rate of 10% is used in the study. The generating cost amounts to US$ 0.08 per kWh. This is shown in Table 7-5.

Table 7-2: Technical parameters

Capacity (MW)	5.1 (0.85 x 6)
Capacity factor (%)	30
Lifespan (years)	20
Annual energy generation (GWh)	13.4
Total generation (GWh)	268.06

Table 7-3: Capital costs (2004 prices)

Item	US$/kW
Equipment	1,120
Civil	70
Engineering	40
Erection	100
Contingency	70
TOTAL	1,400

Table 7-4: O&M costs (2004 prices)

Item	US$ cents/kWh
Fixed O&M	0.66
Variable O&M	0.26
Fuel cost	-
TOTAL	0.92

Table 7-5: Investment and generating costs (2004 prices)

Capital costs (million US$)	7.14
Generating costs (US$ cents/kWh)	7.2

7.1.2 10 MW Solar Thermal Power Plant

Solar energy resources are evenly distributed in the country though the Highlands have higher solar irradiation levels than the coastal areas. For all potential locations in the country, however, direct solar irradiation levels are high and sufficient to sustain large-scale energy generation. Large-scale solar energy power development could be implemented through concentrated solar power (CSP) systems. Though CSP technologies could be installed in several sites in the country, the most economic option is to integrate CSP technologies with existing steam and single cycle power plants.

As a development strategy, the study proposes to initiate a small-scale CSP project of around 10 MW integrating it in one of the steam or gas turbines power plant. As the country gains experience on CSP power operation, large-scale projects, around 50 MW each, could be developed in 2015 and 2020.

7.1.2.1 Technology

Yemen's average direct normal irradiation (DNI) ranges from 1900 – 2500 kWh/m^2/year which is sufficiently high to generate electricity from solar thermal power plants. The DNI of the highland region is far higher than these national averages.

Solar thermal power plants, also called as Concentrating Solar Power (CSP) plants, produce electricity in much the same way as conventional power stations. The difference is that they obtain their energy input by concentrating solar radiation and converting it to high-temperature steam or gas to drive a turbine or motor engine.

Four main elements are required: a concentrator, a receiver, some form of transport media or storage, and power conversion. Many different types of systems are possible, including combinations with other renewable and non-renewable technologies, but the three most promising solar thermal technologies are: parabolic trough, parabolic dish, and power tower. Parabolic trough plants are currently the most mature CSP technology.

Parabolic trough-shaped mirror reflectors are used to concentrate sunlight on to thermally efficient receiver tubes placed in the trough's focal line. A thermal transfer fluid, such as synthetic thermal oil, is circulated in these tubes. Heated to approximately 400°C by the concentrated sun's rays, this oil is then pumped through a series of heat exchangers to produce superheated steam (Figure 7-2). The steam is converted to electrical energy in a conventional steam turbine generator, which can either be part of a conventional steam cycle or integrated into a combined steam and gas turbine cycle.

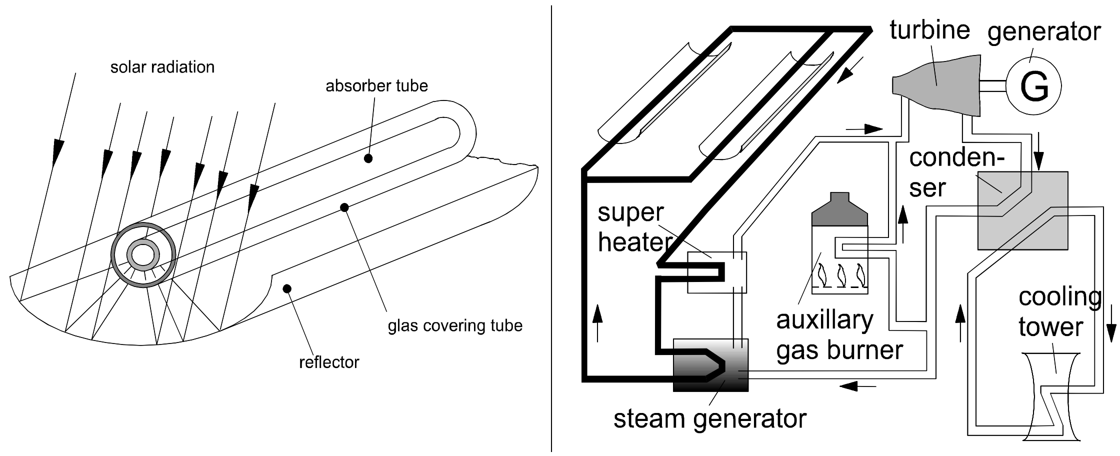


Figure 7-2: left: set up of a parabolic trough collector with absorber tube, right: Schematic of a parabolic trough solar power plant

7.1.2.2 Costs

Integrating a CSP plant in either a steam or combined cycle power plant needs further analysis related to the technical conditions of the existing power plants. In this analysis, a stand-alone system is being used to derive a benchmark figure for CSP generation costs.

Two 10 MW systems are being analyzed in the study: one with thermal storage and the other without storage. The unit without storage is assumed to have lower capacity with annual full operating hours of only 1750 while the one with thermal storage is assumed to have a full load-hours operation of more than 4700. Annual electricity generation from both plants are 17.52 and 47.3 GWh, respectively. The technical parameters of the project are summarized in Table 7-6.

Capital investment and O&M costs are also taken from the World Bank sponsored study on Technical and Economic Assessment of Renewable Energy Technologies. The CSP technology and cost data from this study is based on the global review undertaken by NREL and studies in the Middle East and Africa Region. These are summarized in Table 7-7 and Table 7-8.

The unit with thermal storage requires higher capital investment costs of around US$ 49 million but its total generation costs is only around US cents 13/kWh. Conversely, the unit without thermal storage will only require US$ 25 million as capital investments but the average generation cost is higher at around US$ cents 18.45/kWh (Table 7-9).

Among the renewable energy technologies for grid electrification assessed in the study, CSP at present has the highest cost of generation. CSP costs are however expected to decline in the medium term due to cheaper costs related to solar collector systems, mirror costs, storage costs as well as other technological improvements and economies of scale.

Table 7-6: Technical parameters

Item	Without thermal storage	With thermal storage
Capacity (MW)	10	10
Capacity Factor (%)	20	54
Lifespan (years)	30	30
Annual generation (GWh/year)	17.52	47.3
Total generation (GWh)	525.6	1419.12

Table 7-7: Capital costs (2004 prices)

Item	Without thermal storage (US$/kW)	With thermal storage (US$/kW)
Equipment	850	2000
Civil	200	400
Engineering	550	920
Erection	600	1150
Contingency	250	310
TOTAL	2,450	4,780

Table 7-8: O&M costs (2004 prices)

Item	Without thermal storage (US$ cents/kWh)	With thermal storage (US$ cents/kWh)
Fixed O&M costs	3.01	1.82
Variable O&M costs	0.75	0.45
TOTAL	3.76	2.27

Table 7-9: Investment and generation costs (2004 prices)

Item	Without thermal storage	With thermal storage
Investment costs (US$ million)	24.5	47.8
Generation costs (US$ cents/kWh)	18.45	12.99

7.1.3 5 MW Geothermal Power Plant

The resource assessment study indicates that the country has a huge potential for geothermal energy. Volcanic areas in the Yemen Trap Plateau particularly the Dhamar region have the highest potential for large-scale geothermal power development. In addition, the Ministry of Water and Environment in partnership with a German geological institute is initiating a project to analyze in detail the geothermal potential in the region around Al Lisi volcano and to drill several wells around this region.

Since risks associated with geothermal development (particularly in site development) are high, a small-scale power development of 5 MW is initially proposed. Given also the complexity of site exploration and development, this power plant could be realistically implemented in 2015. Once established, a 50 MW geothermal power plant could be developed in the same region.

7.1.3.1 Technology

Geothermal Systems

The most common way to exploit geothermal resources is to drill a well into covered aquifers with good permeability. Aquifer means a water-bearing layer of the earth, filled with natural water. Covered aquifers are not influenced by infiltrations and thus there is no chemical and temperature mixing to be expected. Good permeability allows transport of enough fluid to the aboveground without using too much energy for pumping. Aquifers may contain liquid water and steam at different percentages. If the pressure in the aquifer is high enough, the fluid flows aboveground by itself. To increase the mass flow it is possible to install a pump aboveground. Otherwise a borehole pump is installed in the production well.

Another way to exploit geothermal energy is called the Hot Dry Rock system. Solid rocks (mostly granite) without (or with few) water inside are used. Structured granite is often found at higher depths. At this depth in Yemen, the temperature could range from 300 °C to 350 °C. A multi-well system is installed by drilling. With high hydraulic pressure from pumping water into the wells the granite is fractured. These fractures build up the connection between the wells. Thus an enormous heat exchanger is generated to transfer the heat to water as the passing working fluid. Therefore water from the surface is pumped into the depth, heated in the rock heat exchanger and lifted up back to the surface at very high temperatures. Heat is then used for power generation. Hot Dry Rock is currently under development and shows good opportunities to become a common technology in the future.

An alternative option is to use structures which are not as solid as granites in Hot Dry Rock systems and which have no adequate permeability by nature. Scientists are on their way to develop methods to stimulate them with hydraulic techniques and to avoid closures after depressurising. These techniques are adopted on sites in Germany and Canada.

Geothermal Electric Power Systems

Assuming a temperature of the earth near the surface of 20 °C and a geothermal gradient of 60°C/km, the 200°C temperature can be reached in a depth of 3,000 meters. A temperature of 200°C is a proper basis to generate electrical energy.

There are different existing techniques for geothermal power generation. At temperatures of 90°C, or above, there are systems capable of converting geothermal heat to electrical power. As an overview this may be divided into three classes:

- Classical power generation. It follows the Clausius-Rankine-Cycle and is used in most conventional power generation plants. After drilling a well, dry steam (no droplets of liquefied water in it) coming from earth is used to power a turbine. The turbine drives the generator and electrical power is generated. Sometimes at the end of the process the steam is blown of, sometimes it condenses and is re-injected into the earth. This kind of energy generation needs (mostly) dry steam, often at temperatures from 200°C and above. With higher temperatures the efficiency increases.

- Steam flash. This technique is used for liquefied geothermal fluids and for fluids with percentages of steam and liquid. The heat from the earth is transported with that fluid. The temperature often reaches 200°C and the fluid is under pressure. After transporting the water aboveground into a container and after depressurising only with small amount, the steam is separated from the liquid phase. In addition, a part of the liquid fluid changes its thermodynamic state to steam. The steam is now used in a Clausius-Rankine-Cycle. The remaining fluid can be handled in another container in the same way at a lower pressure and at a lower temperature of the steam. This steam is given to the turbine at another inlet. This configuration is called double steam flash. There may be more flash processes depending on the resulting steam temperature. All fluids remaining from the flash process(es) and from the condensation, are re-injected into the wells.
- Binary cycle. This approach separates the geothermal water from the technical devices. Geothermal heat is conducted via heat exchanger into the process medium. This process medium is an organic based medium, for example pentane. The advantage is that organic medium boils at low temperatures. The steam of the organic medium is transformed to electrical energy via Rankine cycle. This technique therefore is called Organic Rankine Cycle (ORC). It runs with geothermal water temperatures of 90°C or higher and its process efficiency rises with rising fluid temperature.

  Another technique using low temperatures to generate electrical power is called the Kalina Cycle. The advantage of Kalina, in comparison with ORC is that there is not only one temperature for steam generation but a range of temperatures. Various studies simulated and compared Kalina and ORC processes. The results showed that Kalina has little advantages at temperatures below 150 °C. At higher temperatures ORC yield better results. At present, there are only few plants constructed with Kalina Cycle.

The selection among different techniques is dependent on the characteristics of the geothermal reservoir. The temperature of the geothermal water, the steam content, the content of other ingredients like salt, dissolved solids or non-condensable gases are some of those parameters.

7.1.3.2 Costs

The geothermal resource assessment study indicates that the Tawilah Sandstone layer offers the best opportunity for extracting geothermal heat using the conventional geothermal system. For a 5 MW geothermal power plant, this may require around 3-4 wells with an average depth of 2000 meters.

The study simulates two options for a geothermal power plant in Yemen: binary and flash hydrothermal power plants. For reservoir temperature ranging from 125 – 170°C, a binary system is recommended while for higher than 170°C, flash technology is the most optimal. The technical parameters of these plants are summarized in Table 7-10.

Capital costs by phases of development and the O&M costs are also summarized in Table 7-11 and Table 7-8, respectively. Again, these are average costs from international projects and studies on geothermal power plant development. The total investment costs and generation costs are summarized in Table 7-13. The flash technology offers the lowest investment costs as well as generation costs. The decision however to select type of geothermal electric power system depends manly on the geologic and geothermal conditions of the sites.

Table 7-10: Technical parameters

Item	Binary	Flash
Capacity (MW)	5	5
Capacity Factor (%)	85	90
Reservoir temperature	125 – 170°C	> 170 °C
Lifespan (years)	30	30
Annual generation (GWh/year)	37.23	39.42

Table 7-11: Capital costs by development phase (2004 prices)

Item	Binary (US$/kW)	Flash (US$/kW)
Exploration	320	240
Confirmation	470	370
Main wells	710	540
Field, other	120	60
Power plant	2120	1080
Contingency	190	120
TOTAL	3930	2410

Table 7-12: O&M costs (2004 prices)

Item	Binary (US$ cents/kWh)	Flash (US$ cents/kWh)
Fixed O&M costs	1.90	1.50
Variable O&M costs	-	-
TOTAL	7.50	4.74

Table 7-13: Investment costs and generation costs (2004 prices)

Item	Binary	Flash
Capital investment costs (US$ million)	19.65	12.05
Levelized capital costs (US$ cents/kWh)	5.60	3.24

7.1.4 3 MW Landfill Gas Power Plant

Among biomass energy resources, gas from municipal solid waste landfills could also potentially be exploited for power generation. These are however confined to big cities in Yemen particularly Sana'a, Aden, Taiz, and Al Hodeidah where large scale municipal solid waste are generated, collected and deposited in designated landfill/dump sites.

Sana'a has the highest amount of annual solid waste generation and its current landfill site could be potentially developed. The resource assessment study indicates that a 3 MW generation capacity could be immediately develop from the existing sites. Landfill sites in other big cities could also be developed and the resource study identified capacities of around 1 MW each which could be developed by 2014.

Landfill development in the major cities must also be developed in coordination with various stakeholders such as the local government, the Ministry of Water and Environment as well as the local communities.

7.1.4.1 Technology

The organic materials of the municipal solid waste produce various types of gases when dumped, compacted and covered in landfills. Anaerobic bacteria decompose these organic materials and in the process, carbon dioxide and methane gases are generated. Carbon dioxide will often leached out because it is soluble to water while methane will likely to migrate out since it is less soluble in water. The methane yield of the landfill depends on the composition of the waste, the chemical and the collection processes.

Landfill energy collection facilities capture the methane and burn it for energy production. The process of the collection process and the production of energy is shown in Figure 7-3. In producing electricity, the methane gas is fed directly to gas engines to generate power.

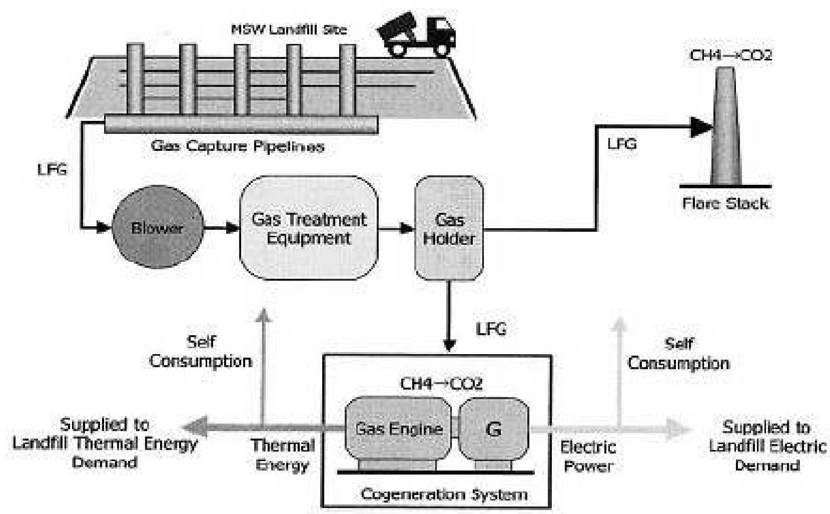


Figure 7-3: Municipal Landfill Gas Production System

7.1.4.2 Costs

The resource assessment study estimates that with the volume of waste collected and dumped in designated site in Sana'a could potential generate more than 3 MW of electric power. The study assumes technical and cost parameters based on international projects on landfill gas power generation. Capacity factor is assumed at 80 percent while the project lifespan is 20 years. The summary of the technical assumptions is shown in Table 7-14. The estimated annual generation of the power plant amounts to 21.02 GWh.

The capital and O&M costs used in the study are shown in Table 7-15 and Table 7-16. Again, these figures represent range of values for various projects globally. The capital investment costs for the 3 MW power plant amounts to US$ 942 million. The average generation cost is estimated to be US$ 0.65/kWh. This is shown in Table 7-17.

Table 7-14: Technical parameters

Capacity (MW)	3
Capacity factor (%)	80
Lifespan (years)	20
Annual energy generation (GWh)	21.02
Total generation (GWh)	420.48

Table 7-15: Capital costs (2004 prices)

Item	US$/kW
Equipment	1390
Civil	900
Engineering	90
Erection	600
Contingency	160
TOTAL	3140

Table 7-16: O&M costs (2004 prices)

Item	US$ cents/kWh
Fixed O&M	0.11
Variable O&M	0.13
Fuel cost	1.00
TOTAL	1.24

Table 7-17: Investment and generating costs (2004 prices)

Capital costs (million US$)	9.42
Generating costs (US$ cents/kWh)	6.50

7.2 Off-grid Rural Electrification Options

Among renewable energy resources evaluated in the study, solar energy is the only abundant resource in Yemen that could be exploited to provide energy services to rural and remote households and communities that could not be reached by grid extension.

Off-grid areas are being identified in the National Rural Electrification Strategy Study. The study will also classify households and villages that can be covered by the grid in the short, medium and long-terms. Results of this study will be useful in designing an off-grid rural electrification program.

Stand alone solar PV systems such as the solar home systems (SHS) are often the most viable and the least-cost option in supplying energy services in off-grid areas. A solar home system typically consists of a solar module consisting of an array of solar cells, and balance of system composed of electricity conditioning and/or controlling device such as inverter or regulator, electricity storage device such as battery (except in grid applications), and support structure and cabling connecting the power system to either the load or the grid.

SHS are within the class size range of 10 – 100 W of solar PV applications. These technologies are currently available in Yemen. Sizes available in the market are 40 W and 70 W.

Another study, Market Study and Pipeline Development for Solar PV, is also being implemented in Yemen. The study undertakes solar PV market assessment and characterization, develops five replicable project pipelines, and provides broad design of technical details, investment requirements and institutional arrangements for the project.

8 Conclusion

The Republic of Yemen is endowed with significant amount of renewable energy resources. Resources with potential for large-scale exploitation include wind, solar and geothermal energies. To some extent, the energy conversion of municipal solid waste through landfill gas could potentially sustain commercial scale development (Table 8-1).

Table 8-1:Renewable energy resource potential in Yemen

Resources	Technical Potential
Wind energy	15,237 MW
Solar energy	average annual radiation 5.2 – 6.8 kWh/m^2/day *Identified applications* 53.2 MW (Solar home systems) 1,824 MW (Concentrating solar power) 332.7 MW (Solar water heating)
Geothermal	125-250 MW (Dhamar region) 28,500 MW (Other regions)
Small hydropower	11-30 MW
Biomass	7.53 MW (landfill gas) 1.04 MW (sewage sludge)

More than 500 MW of installed capacity consisting of more than 20 projects from wind, solar, geothermal and landfill gas could be potentially developed in the country given the right enabling environment between now and 2020 (Table 8-2). These projects could generate a total of more than US$ 900 million of capital investments in the country (Table 8-3).

Similarly, solar PV applications could be used to provide energy services in the rural areas. Two separate studies, the National Rural Electrification Strategy Study, and Market Study and Pipeline Development for Solar PV, are being carried out in the country. The results of these studies would be the basis for determining the potential of solar energy resources in supplying electricity services in rural and remote communities in Yemen.

Task 2 of this study addresses the rationale why it is necessary to promote the utilization of grid and off-grid renewable energies in Yemen and formulates a national strategy to achieve the target 500 MW of renewable energy generation and the targeted volume of solar home systems to be distributed in rural areas. In addition, an action plan elaborating specific actions to be undertaken by the Government over the next ten years to support the realization of these goals will be covered in Task 3 of this study.

Table 8-2: Renewable energy power development 2010-2020.

Year	Wind (MW)	Geothermal (MW)	Solar (MW)	Landfill Gas (MW)	Total (MW)
2010	10 [1] (Mokha/Hodeidah)			3 [1] (Sana'a)	**13**
2011					
2012	100 (Aden/Mokha)		10 [1]	3 (Aden, Taiz, Hodeidah)	**113**
2013					
2014	100 (Aden/Mokha)	5 [1] (Dhamar)			**105**
2015			50		**50**
2016	50 (Mokha or Aden)				**50**
2017					
2018					
2019					
2020	80 (4 sites in Highlands)	50 (Dhamar)	50		**180**
Total	**340**	**55**	**110**	**6**	**511**

Note: [1] could be developed as pilot projects with public sector financing

Table 8-3: Investment requirement of renewable energy project pipeline

Technology	Capacity (MW)	Capital Costs (million $/MW)	Investment Costs (million $)
Wind	340	1.6	544
Geothermal	55	2.0	110
Solar Thermal	110	2.45*	269.5
Landfill Gas	6	3.14	18.84
Total	511		942.34

* parabolic trough technology with thermal storage.