



PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

NET ENERGY ANALYSIS OF HYBRID CONCENTRATED SOLAR THERMAL POWER PLANTS IN CHILE: A SELECTION METHODOLOGY FOR OPTIMAL PLANT LOCATION BASED ON SUSTAINABILITY ATTRIBUTES.

TERESITA JESUS LARRAIN MUJICA

Tesis para optar al grado de
Magíster en Ciencias de la Ingeniería

Profesor Supervisor:
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Santiago de Chile, Enero, 2009

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A mi madre.

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CONTENTS

	Pág.
DEDICATION	II
ACKNOWLEDGEMENTS	III
CONTENTS	IV
LIST OF TABLES	VII
LIST OF FIGURES	IX
NOMENCLATURE.....	XIII
LIST OF ACRONYMS	XVII
RESUMEN.....	XVIII
ABSTRACT	XIX
1. INTRODUCTION	1
1.1 Energy in Chile	3
1.2 Potential in Chile for CSP plants	7
1.3 Summary	9
2. CONCENTRATED SOLAR POWER TECHNOLOGIES	11
2.1 Concentrated solar power principles	11
2.2 Concentrated solar power technologies overview.....	13
2.3 Selection of the most convenient alternative for Chile	15
2.4 Parabolic trough collector power plants.....	16
2.4.1 Solar field properties.....	18
2.4.2 Parabolic trough collector	18
2.4.3 Power generation system of a PTC plant.....	19
2.5 Parabolic trough collector power plants history and development	21
2.6 Summary	22
3. THESIS OBJECTIVES	23

4.	BEAM SOLAR RADIATION ESTIMATES	27
4.1	Selected locations.....	27
4.2	Monthly average daily radiation available at selected locations.....	28
4.3	Utilizability for a parabolic trough collector.....	29
4.4	Estimation of daily radiation from monthly average	32
4.5	Estimation of beam component of daily radiation	34
4.6	Estimation of hourly radiation I from daily data	37
4.7	Summary	38
5.	MODELING OF THE PTC HYBRID PLANT.....	40
5.1	CSP plant configuration	40
5.2	First approximation to backup requirements.....	43
5.3	Solar field analysis: collector energy balance	44
5.4	Backup requirement	52
5.5	EES Model	53
5.6	Summary	54
6.	NET ENERGY ANALYSIS	55
6.1	NEA history	55
6.2	Process analysis.....	56
6.3	Input-Output analysis.....	57
6.4	Net energy analysis as a evaluation tool	58
6.5	Net energy analysis for PTC power plants in Chile.....	59
6.6	System boundary	60
6.7	Energy outputs generated by the plant.....	61
6.8	Energy requirement of the plant.....	62
6.8.1	Human labor energy requirement	64
6.8.2	Energy content of materials	66
6.8.3	Fuel cycle.....	68
6.8.4	Electrical energy requirement.....	77
6.8.5	Transportation energy requirement.....	79
6.9	Sustainability indicators: EROI and Energy payback time.....	79
6.10	Summary	80
7.	RESULTS AND DISCUSSION.....	82

7.1	Direct solar radiation for each location	82
7.2	First approximation to obtain a estimation of a backup fraction	84
7.3	Comparison of backup results from EES model	85
7.4	Backup requirement obtained using an artificial month	87
7.5	Fuel cycle energy requirement	89
7.5.1	Delivery	93
7.5.2	Production, storage and processing	96
7.5.3	Exploration	96
7.6	Component manufacturing and plant construction phase	97
7.7	Plant operation and maintenance phase	100
7.8	Decommissioning, materials recycling and refurbishment	101
7.9	Net energy for each location	102
7.10	Sustainability indicators: EROI and Energy payback time	105
7.10.1	Energy return over investment, EROI	106
7.10.2	Energy payback time (EPT).....	108
8.	CONCLUSIONS	113
8.1	Recommendations for future works	119
	REFERENCES.....	121

LIST OF TABLES

	Pág.
Table 1-1: Solar radiation for different locations with CSP projects and for Chile (data from Duffie and Beckmann, 2006).....	9
Table 2-1: Comparison of CSP technologies (from Kaltschmitt, 2007).....	16
Table 4-1: Latitude and longitude for each location	27
Table 5-1: Properties of the ET-100 parabolic trough collector	42
Table 5-2: Approximation of average wind velocity for each location (from Sarmiento, 1995)	48
Table 6-1: Energy expenditure for different groups of workers	65
Table 6-2: Energy content for different materials.....	67
Table 6-3: Production/delivery ratio for NG in Chile	72
Table 6-4: CSP plants locations nearest NG Pipelines properties.	72
Table 6-5: Estimations of EROI for natural gas in USA	76
Table 6-6: Primary energy conversion factors for SING matrix.....	78
Table 7-1: Monthly backup for each location obtained from EES model, using a month with identical days and an artificial month.....	86
Table 7-2: Monthly backup for each location, obtained using an artificial month and total monthly energy required.....	88
Table 7-3: Monthly backup, as percentage of total energy required.....	88
Table 7-4: Fuel cycle energy requirements, 12 hours of operation.....	90
Table 7-5: Fuel cycle energy requirements, 24 hours of operation.....	90

Table 7-6: Pipeline materials energy cost for each location.	93
Table 7-7: Pipeline construction energy cost for each location.	94
Table 7-8: Compressor energy costs.	94
Table 7-9: Transport fuel losses for each location, sunlight hour operation.....	95
Table 7-10: Transport fuel losses for each location, 24 hours operation.	95
Table 7-11: Fuel delivery ER for each location.	95
Table 7-12: PS&P ER for each location.	96
Table 7-13: Exploration energy requirement for each location.	97
Table 7-14: Component manufacturing and plant construction ER.....	98
Table 7-15: Energy requirement for materials transport.....	99
Table 7-16: ER for Component manufacturing and plant construction phase.....	100
Table 7-17: Energy requirement for Operation and Maintenance phase.	101
Table 7-18: Decommissioning, material recycling and refurbishment ER.....	102
Table 7-19: Energy balance and Net energy for sunlight hours operation mode.....	103
Table 7-20: Energy balance and Net energy for 24 hours operation mode.	104
Table 7-21: EROI for all locations, in both operation modes.	106
Table 7-22: EPT for all locations, in both operation modes.	109
Table 7-23: EPT (y) as function of operation years (x).	111

LIST OF FIGURES

	Pág.
Figure 1-1: Chilean Historical consumption of Primary Energy, 1978-2007 (from CNE, 2007).	4
Figure 1-2: North Chile generation system fossil fuel composition (from CNE, 2007)....	5
Figure 1-3: Chilean Historical Energy dependence, in energy terms since 1999 (from CNE, 2007).	5
Figure 1-4: Solar energy maps for Chile: ground station measurements (from Sarmiento 1995) and satellite estimations (from Ortega, Escobar and Colle 2008) of daily radiation on yearly mean.	8
Figure 2-1: Andasol 1 PTC Plant in spring 2008 (from Solar Millennium webpage).....	13
Figure 2-2: PS10 and PS20 central receiver plant (from Abengoa Solar webpage).....	14
Figure 2-3: Parabolic trough in PSA, Almería.....	17
Figure 2-4: Absorber of a parabolic trough collector.....	19
Figure 2-5: Two basic designs for PTC.	20
Figure 4-1: Map with selected locations in northern Chile.....	28
Figure 4-2: Daily radiation on monthly mean at selected locations.....	29
Figure 4-3: Cumulative distribution curve for hourly beam radiation over average hourly beam radiation, for Latitude 19.08 South, in February, for the hour pair 10 to 11.....	30
Figure 4-4: Cumulative distribution curve for hourly beam radiation over average hourly beam radiation for Latitude 19.08 South, in February, for the hour pair 10 to 11.....	31

Figure 4-5: H for January, based on $\bar{H} = 25.2 MJ / m^2 day$ for Location 1.	33
Figure 4-6: H for June, based on $\bar{H} = 17.1 MJ / m^2 day$ for Location 1.	34
Figure 4-7: Global $\bar{H}$ and beam $\bar{H}_b$ monthly mean radiation at location 1.....	35
Figure 4-8: Global $\bar{H}$ and beam $\bar{H}_b$ monthly mean radiation at location 2.....	36
Figure 4-9: Global $\bar{H}$ and beam $\bar{H}_b$ monthly mean radiation at location 3.....	36
Figure 4-10: Global $\bar{H}$ and beam $\bar{H}_b$ monthly mean radiation at location 4.....	37
Figure 5-1: Solar DSG plant configuration with back-up system.....	42
Figure 5-2: DSG plant configuration with back-up system (dimensions in meters).....	43
Figure 5-3: Resistance model of the heat losses between the HTF and the absorber.	49
Figure 5-4: Energy balance in a collector segment.	50
Figure 6-1: Energy inputs and outputs for the CSP power plant	61
Figure 6-2: North Chile NG Pipeline system. (CNE, 2008)	69
Figure 6-3: Central Chile NG Pipeline system. (CNE, 2008).....	70
Figure 6-4: Total production from 2000 to 2007 for NW and Neuquén basins in thousand millions of m^3	71
Figure 6-5: Process efficiency v/s EROI, for NG production.	74
Figure 7-1: Hourly global radiation for different days of January at Location 1.....	83
Figure 7-2: Hourly beam radiation for different days of January at Location 1.	84

Figure 7-3: First approximation of average daily backup for each month.....	85
Figure 7-4: Backup for each location obtained from EES model, using a month with identical days and an artificial month, and monthly mean radiation.	87
Figure 7-5: Average daily backup for each month.....	89
Figure 7-6: Composition of fuel cycle energy requirements for each location, Sunlight hours operation.....	91
Figure 7-7: Composition of fuel cycle energy requirements for each location, 24 hours operation.....	91
Figure 7-8: Fuel cycle energy requirement for each location, comparison between sunlight hours operation and 24 hours operation.	92
Figure 7-9: Composition of fuel cycle energy requirement for location 3, sunlight hours operation.....	92
Figure 7-10: Life cycle inputs for Location 1, in 12 hours operation mode.	104
Figure 7-11: Net energy for all locations, in both operation modes.	105
Figure 7-12: Net energy for all locations, in both operation modes compared with a traditional NG power plant.	107
Figure 7-13: Net energy for all locations, as function of the Backup fraction and EROI.	108
Figure 7-14: EPT for all locations, as function of the operation years, for sunlight hours only operation.....	109
Figure 7-15: EPT for all locations, as function of the operation years, for sunlight hours only operation.....	110

Figure 7-16: EPT for all locations, as function of the operation years, for continuous operation.....110

Figure 7-17: EPT for all locations, as function of the operation years, for continuous operation.....112

Figure 8-1: Monthly backup, in percentage for all locations.115

Figure 8-2: Rank of the analyzed locations for sunlight operation mode.116

Figure 8-3: Net energy for all locations, in both operation modes compared with a traditional NG power plant.117

NOMENCLATURE

a :	Collector aperture
A_{sf} :	Solar field collector area
bv :	Book value of a product
C_p :	Heat capacity of the HTF
C_j :	Cost of the component j
CE :	Cumulative energy
$days$:	Days of operation for year
d :	Distance in km
D_i :	Absorber inner diameter
D_o :	Absorber outer diameter
$\dot{E}_{solar}$:	Energy input to the plant from the solar radiation
E_{return} :	Energy return
$E_{invested}$:	Energy invested
E_i :	Energy contained in a component i
$E_{i,AB}$:	Energy contained in component i required for period or process AB
EC :	Electric consumption
ER_i :	Energy requirement of a component i
ER_{AB} :	Energy requirement for AB process
$ER_{i,AB}$:	Energy requirement for component i during process AB
EM_i :	Emergy of component i
$E_{f,p}$:	Energy content of fuel production required for the plant
$E_{f,d}$:	Energy content of total fuel delivery to plant
f :	Fractional time
f_i :	Load factor of the plant
$\bar{H}$:	Daily total radiation, monthly mean
H :	Daily total radiation
$\bar{H}_o$:	Monthly mean extraterrestrial radiation

$h_{conv,HTF \rightarrow abs,out}$	:Heat transfer coefficient of the convection between the HTF and the inner absorber surface
h_i :	Fluid enthalpy in point i
h_d :	Hours of operation per day
I :	Hourly radiation
I_c :	Critical radiation level
K_T :	Daily clearness index
$\bar{K}_T$:	Clearness index, monthly mean
L :	Collector length
$\dot{m}$:	Mass of the HTF
m_{has} :	Mass of high alloy steel (in tons)
m_i :	Mass of component i
$n_{hl,k}$:	Number of human labor of the type k required annually
P :	Power of the plant
pcf :	Primary conversion factor
$\dot{Q}_{fluid}$:	Fluid useful energy gain
$\dot{Q}_{abs}$:	Energy absorbed by solar radiation
$\dot{Q}_L$:	Energy loss
q_L :	Energy loss per unit area of collector
r_t :	Ratio of hourly total to daily total radiation
r_d :	Ratio of hourly diffuse to daily diffuse radiation
$r_{p/d}$:	Fuel production to delivery ratio
T :	Temperature
T_i :	Transportation technology energy use
U :	Overall heat transfer coefficient between the working fluid and the outer surface of the absorber tube
V :	Wind velocity

$X_c :$	Dimensionless critical radiation level
$x_i :$	Steam quality in point i
$y :$	Years of operation

Greek letters

$\alpha :$	Absortance
$\delta :$	Declination
$\varepsilon_{ab} :$	Absorber emissivity
$\varepsilon_i :$	Energy intensity for sector i
$\varepsilon_{AB} :$	Energy intensity for process AB
$\phi_h :$	Utilizability
$\gamma :$	Intercept factor
$\eta_a :$	Plant availability factor
$\eta_{coll} :$	Collector efficiency
$\eta_{f,PR} :$	Fuel production efficiency
$\eta_p :$	Parasitic loss coefficient
$\eta_{pp} :$	Power plant efficiency
$\eta_{sc} :$	Steam cycle efficiency
$\eta_{sf} :$	Efficiency of the solar field
$K_{\gamma\alpha} :$	Incidence angle modifier of the collector
$k_{abs} :$	Absorber conductivity
$\rho :$	Specular reflectance
$\tau :$	Transmittance
$\omega :$	Hour angle

Subscripts

<i>a:</i>	Dry bulb
<i>abs:</i>	Absorber
<i>b:</i>	Beam
<i>bt:</i>	Beam radiation on the moving surface of the collector
<i>CO:</i>	Continuous operation
<i>d:</i>	diffuse
<i>DRR:</i>	Plant decommissioning, materials recycling and refurbishment of the location process
<i>DE:</i>	Fuel delivery process
<i>EX:</i>	Fuel extraction process
<i>EXP:</i>	Fuel exploration process
<i>FOP:</i>	Field operation process
<i>f:</i>	Fuel
<i>FP:</i>	fuel processing process
<i>hl:</i>	Human labor
<i>HW:</i>	High intensity work.
<i>LC:</i>	Life cycle
<i>LW:</i>	Light intensity work.
<i>MW:</i>	Medium intensity work.
<i>PC:</i>	Component manufacturing and plant construction process
<i>PO:</i>	Plant operation and maintenance process
<i>PR:</i>	Production process
<i>s:</i>	Sunrise
<i>SO:</i>	Sunlight operation
<i>TR:</i>	Transportation process
<i>VF:</i>	Vent and flare process
<i>W:</i>	Work

LIST OF ACRONYMS

CSP:	Concentrated solar power
DSG:	Direct steam generation
ECL:	Energy carrier limit
EES:	Engineering equation solver
Emergy:	Embodied energy
EM:	Emergy
EPT:	Energy payback time
ER:	Energy requirement
EROI:	Energy return over invested
GHG:	Green house gases
HCE:	Heat collector element
HHV:	High heating value
HTF:	Heat transfer fluid
IPCC:	Intergovernmental panel in climate change
ISCCS:	Integrated solar combined cycle system
I/O:	Input-output
LCI:	Life cycle inventory
NE:	Net energy
NEA:	Net energy analysis
NG:	Natural gas
NPEP:	Net primary energy production
PS&P:	Natural Gas production, storage and processing
PTC:	Parabolic trough collector
SEGS:	Solar electric generating systems
SING:	Northern Chile, interconnected power system

RESUMEN

La política energética chilena intenta promover la eficiencia y sustentabilidad de los sistemas energéticos, objetivos reflejados en la última modificación realizada a la ley de generación eléctrica que establece alcanzar un 5% de participación de energías renovables en la matriz para el año 2010 y un 10% para el 2024. Las plantas de generación de potencia solares son una opción para lograr estas metas, ya que en Chile se presentan excelentes niveles de radiación solar, principalmente en la zona norte donde adicionalmente existen altos índices de claridad y amplias extensiones de terrenos apropiados para este tipo de plantas. La presente investigación estudia el ciclo de vida de una planta solar híbrida mediante un análisis de energía neta con el propósito de obtener y analizar sus atributos energéticos (energía neta, retorno energético sobre la inversión en energía y tiempo de retorno energético) y comparar distintas ubicaciones posibles para su instalación. Para ello se modeló el comportamiento de una planta de 100 MW del tipo colector cilindro parabólico y calculó la fracción de combustible fósil requerido, en función de las medias mensuales de radiación solar para distintas ubicaciones en el norte del país, operando en dos modalidades: durante horas de luz y operación continua. Los resultados obtenidos indican que la planta solar es una fuente energética para todas las ubicaciones analizadas, y que el mayor costo energético tiene relación con el ciclo de vida del combustible fósil utilizado como backup. Cuando la planta opera de manera continua la energía neta aumenta en un 50%, pero la tasa de retorno energético disminuye hasta un 25%, convirtiéndose en un modo de operación menos sustentable desde el punto de vista energético. Basado en los resultados se concluye que la tecnología analizada es fuente energética en el norte de Chile, incluso con la utilización de respaldo fósil. Además se comprueba que el análisis de energía neta permite determinar las condiciones bajo las que los sistemas estudiados son fuente energética, pudiendo ser utilizado para definir ubicaciones y condiciones de operación óptimas para fuentes de energías renovables.

Palabras Claves: Análisis de energía neta, retorno energético sobre la inversión, plantas termosolares, colectores cilindro parabólicos.

ABSTRACT

Chilean energy policy goals attempts to promote efficiency and sustainability in the energy system and these objectives have been considered in the new modification to the Chilean electricity generation law, establishing that generation companies have to reach a 5% of generation from renewable sources by 2010 and a 10% by 2024. Concentrated solar power is an interesting alternative to help achieve those objectives, as it is estimated that northern Chile has high radiation levels, coupled with the high values of the local clearness index and availability of appropriate terrains for this kind of installations. This research studies a hybrid solar power plant lifecycle through a net energy analysis to obtain and analyze its energy attributes (net energy, energy return over investment and energy payback time). By doing this, best locations are determined to install a plant in the Atacama Desert. Monthly means of solar radiation are used in order to estimate the solar fraction for a 100MW parabolic trough collector plant at different locations, for two operation modes: sunlight hours only and continuous operation. Research results indicate that solar power plants are a net energy source in both operation modes for all the analyzed locations and that higher energy costs are related to the fossil fuel backup lifecycle. In the continuous operation mode net energy generated is approximately 50% more than for the sunlight hours only operation mode, but energy return rate decreases 25% becoming a less convenient option from a energy point of view. It is concluded that parabolic trough collector solar power plant technology is a net energy source in north Chile, even if backup from fossil fuels is required. It is estimated that the net energy analysis is a useful tool for determining under which conditions a power plant becomes a net energy source and a more convenient option, and thus can be utilized in order to define best geographical locations and operation conditions for different renewable energy sources.

Keywords: Net energy analysis, energy return over investment, solar power plant, parabolic trough collector systems.

1. INTRODUCTION

The 4th assessment report of the Intergovernmental Panel on Climate Change (IPCC) has confirmed that a global warming process is underway, reflected in global temperature increases, widespread melting of snow and ice reservoirs, average sea level rising, and other consequences (IPCC report, 2007). As described in the report, global average surface temperature has increased approximately 1°C in the last 150 years, and between 1995 and 2006 eleven of these twelve years were the warmest years since 1850. Data from sea levels displays a 72% of growth in the sea level rising rate since 1961 and satellite data confirm a decrease in snow and ice extent. The global warming process is directly related with greenhouse gases (GHG) emissions, which dominate the radiative forcing (change in the difference between the incoming and outgoing irradiance at tropopause for a given climate system) producing for higher concentrations a warming rate increase. The atmospheric concentration of GHG such as CO₂, methane and nitrous oxide which are product of human activities has increased by 70% between 1970 and 2004, with current values far exceeding pre-industrial levels. Then, human activities are the principal cause of these processes, mainly due to the increased use of fossil fuels. Effects of global warming include changes and destruction of ecosystems, increased number of climate-related natural disasters, and potential water and food shortages. As fossil fuel utilization presents serious environmental impacts, climate change may be stopped with the replacement of other energy sources.

An additional issue is that fossil fuels are subject to resource depletion due to its non-renewable condition. This condition is based on the fact that net primary energy production (NPEP) of organic material needed to produce fossil fuels consumed in one year is 420 times the real annual NPP, with a process energy requirement (ER) of 36 times the energy that earth receives from the sun (J. Dukes, 2003), which means that fossil fuel consumption rate is higher than its production rate. As a consequence a peak of fossil fuel production is expected and eventually its depletion (Bentley, 2002). When global fossil fuel production peaking will occur is not known with certainty, but experts

predict that it will happen within the next two decades (Hirsch, 2005; Dorian et al, 2006).

Considering both environmental and depletion issues of fossil fuels, it becomes therefore necessary to find adequate substitutes and plan a transition to other energy sources, which must meet adequate price levels in order to ensure proper access to the population, provide minimum environmental impact, and be available in sufficient quantities in order to satisfy demand thus ensuring security of energy supply (Dorian et al, 2006). These requirements are the basis of sustainable development, which refers to the capability to meet the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). Not only environmental protection is required but also resource conservation. Today's society relies on energy resources for development and it is expected that future generations will as well. As a result, it becomes imperative to optimize resource utilization (preferring high efficiency processes) and to analyze power plants effective potential for production of energy before implementation, to ensure that energy obtained from the new system must be at least equal to his life cycle energy requirements, and guarantees that the same (or more) energy invested today is going to be also available for future generations. For the second objective it is recommended to use the net energy analysis (NEA) tool that will evaluate effective energy production for any productive process.

Transition to renewable sources can be accelerated by governments utilizing adequate policies and instruments that help create incentives for mitigation of GHG emissions and investments in renewable energy technology research and development. An international initiative to reduce global GHG emission is the Kyoto protocol, a protocol of the United Nations Framework Convention on Climate Change (United Nations, 1998) that aims to stabilize GHG emissions establishing legally binding commitments for the reduction with different obligations as the development level of each country.

It is clear that a transition from fossil fuels to a diversified energy matrix with an important contribution from renewable energy sources is a convenient solution for reducing GHG emissions and ensures security of energy supplies. Among renewable energy sources, solar energy is an attractive alternative for some countries, as it takes advantage of a very long term source of energy, the sun. Power generation systems that use solar energy as a source can result in greatly reduced equivalent GHG emissions. Additionally, in most cases these are not subjected to land use issues or controversies since the typical locations for installing these systems are deserts or arid regions, with generally lower population densities.

In this chapter, energy situation in Chile and CSP technologies are presented, in order to analyze the potential for the application of CSP in Chile.

1.1 Energy in Chile

The situation in Chile is similar to the rest of the world: the main energy sources that the country utilizes are oil and its derivatives, coal, and natural gas. Historically, fossil fuels present the higher share in primary energy consumption and it grows in the course of the years, as displayed in Figure 1-1.

Chile relies on fossil fuels for a great percentage of its primary energy consumption. Renewable energy sources in use by the country comprise only hydroelectricity and wood-based biomass. In the best case, renewable energy sources mainly large scale hydroelectricity plants accounts for 24% of primary energy consumption while non-renewable sources account for the other 76%.

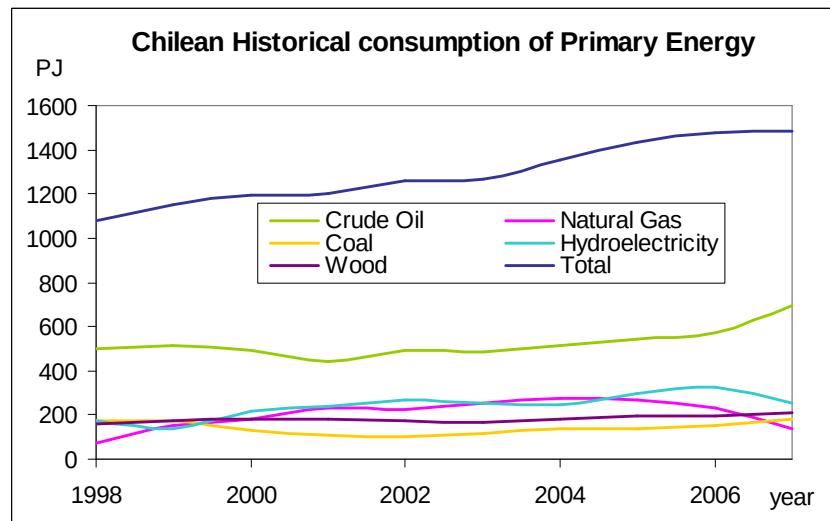


Figure 1-1: Chilean Historical consumption of Primary Energy, 1978-2007
(from CNE, 2007).

In northern Chile interconnected power system (called SING), fossil fuel utilization is alarming with a contribution in 2007 of 99%, and high participation of natural gas (58.6%) and coal (33.5%) as displayed in Figure 1-2. Reduced water resource is the principal cause of this scenario. High energy consumption in northern Chile is related to mining and industrial processes which require continuous operation and energy supply. Therefore, renewable resources may be a solution only when developed as a complement to the system due to resource variability.

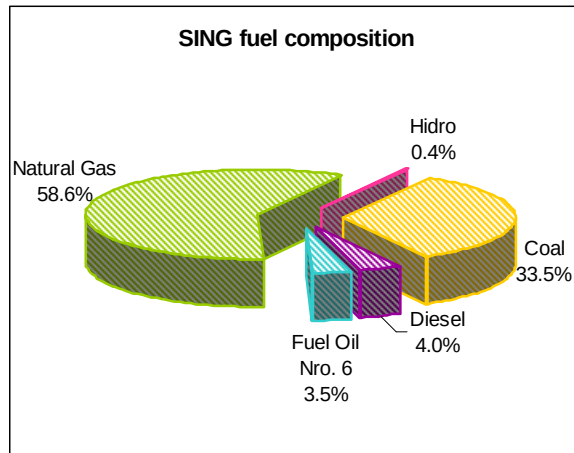


Figure 1-2: North Chile generation system fossil fuel composition (from CNE, 2007).

The principal problem is that Chile does not produce fossil fuels in significant quantities nor does it possess reserves that can be explored and exploited in the future. Chile relies on energy imports to meet its growing energy demand with approximately 70% of energy dependence as displayed in Figure 1-3.

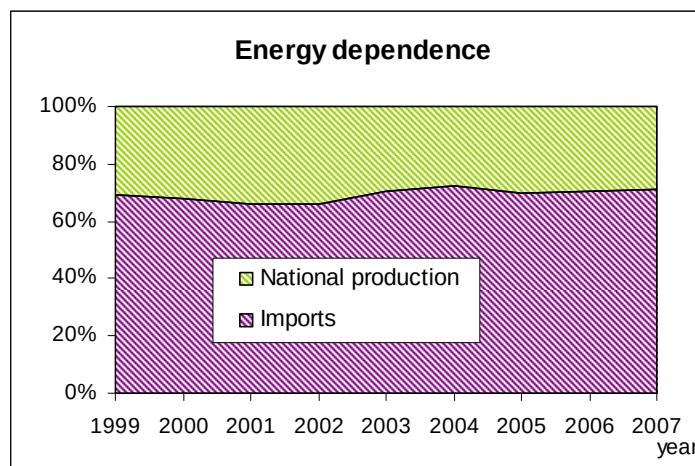


Figure 1-3: Chilean Historical Energy dependence, in energy terms since 1999 (from CNE, 2007).

The supply of natural gas, most of which was imported from Argentina, has steadily decreased from 2006. The available supply from this source is unstable and there have been periods where imports have been negligible. These periods have increased in duration and frequency. This has made Argentinean natural gas an unreliable energy source and also contributed to a fuel switching process to other fossil fuels. In particular, the industry and power generation sectors have switched to diesel and coal, with most of the projected thermoelectric capacity under construction being coal-fired. Thus, Chile is not only maintaining dependence on imported energy but is also switching to more expensive sources with greater environmental impacts and varying prices. The concrete actions that Chile is taking in order to secure energy supply go directly against the sustainable development definition.

It is of critical importance for the country to achieve three primary strategic goals: first, to provide adequate energy supplies in order to continue its economic growth; second, to ensure that imported energy is accessed through international markets to satisfy any requirements that can not be met by internal fuel production; and third, to promote the development of indigenous energy sources at a sufficient rate such as needed for the substitution of imported energy resources in order to improve energy security and reduce energy dependence.

Chile's energy policy promotes efficiency and sustainability in the energy system. These objectives have been reflected in the new modification to the Chilean electricity generation law establishing that generation companies must reach 5% of generation from renewable energies by 2010 and a 10% by 2024 (Ministerio de Economía, 2007). Therefore, in order to maximize Chile's resources utilization all renewable energies should be analyzed. Within renewable energies, solar energy seems a good alternative to develop in Chile mainly because solar radiation available in the country and climatic conditions are better than in other locations where solar energy technologies are in use today. In the next section potential for CSP in Chile is analyzed, considering these particular advantages.

1.2 Potential in Chile for CSP plants

The potential in Chile for CSP plants has not yet being determined. The first step prior to exploiting local energy resources is to determine the available quantities and best locations of where to take advantage of them. In this context it is possible to pronounce that the Atacama Desert in the northern part of the country is one of the best regions for solar energy based on energy density data from several sources (Goswami, Kreith and Kreider 2004, Duffie and Beckmann 2006, Sarmiento 1995, Ortega, Escobar and Colle 2008). Also, the region delivers a high number of clear days during any year, due to the aridity of the Atacama desert, defined as a hyper arid region (Mainguet and Reimer, 1999) with annual average precipitations lower than 50mm per year (INE, 2005). In fact, clear skies conditions have attracted many astronomical observatories.

This study has considered solar radiation maps presented by Ortega, Escobar and Colle (2008), which are derived from satellite image processing by means of the GL 1.2 radiative transfer model from the Brazilian Space Institution INPE. Validation of the GL 1.2 model was obtained by comparison with 80 ground stations of the Brazilian solarimetric network, and good agreement was found (Pereira et al, 2006). The comparison with ground stations resulted accurate with a monthly mean deviation less than 10 W/m^2 and a standard deviation of monthly data of 20 W/m^2 (Ceballos and Bottino, 2004). Figure 1-4 shows a comparison between the satellite estimations and ground station measurements compiled by Universidad Técnica Federico Santa María, resulting from the data acquired by 89 pyranographs and Stokes-Campbell devices, spanning the period from 1961 to 1984.

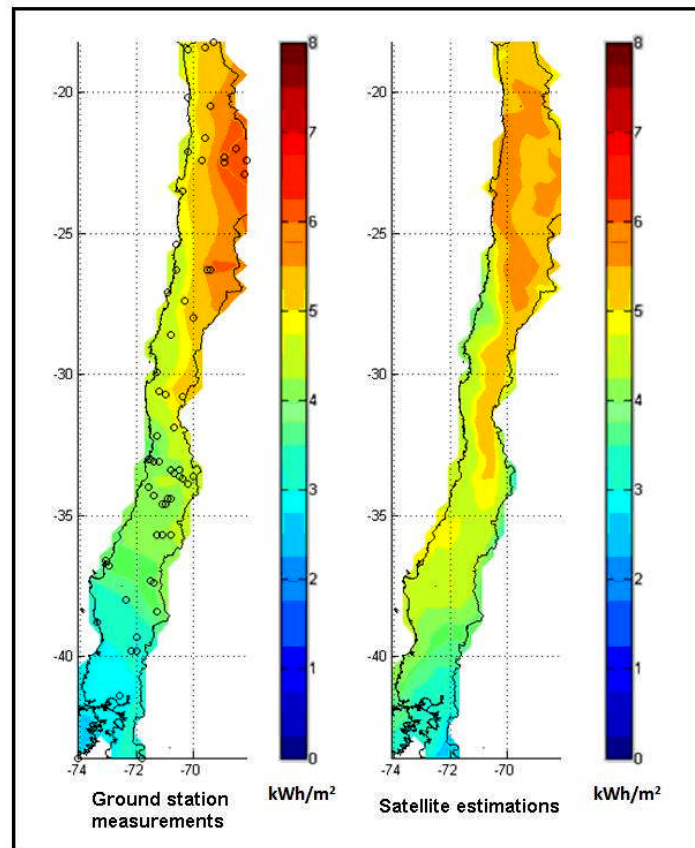


Figure 1-4: Solar energy maps for Chile: ground station measurements (from Sarmiento 1995) and satellite estimations (from Ortega, Escobar and Colle 2008) of daily radiation on yearly mean.

Most of this ground station data has a relatively high uncertainty level, thus making it unsuitable for energy planning at the national policy level (Pereira et al, 2006). However, the data is useful for solar water and air heater evaluation, and is readily available in Sarmiento (1995).

Yearly mean radiation reaches 6 kWh/m^2 per day in some regions in north Chile, and is higher than yearly mean radiation in some locations where CSP technologies are in use today, such as California where it reach 5.86 kWh/m^2 or Almeria, in Spain, where values approach to 4.8 kWh/m^2 as shown in Table 1-1.

Table 1-1: Solar radiation for different locations with CSP projects and for Chile (data from Duffie and Beckmann, 2006).

Plant	Location	Radiation kWh/m²
Plataforma Solar de Almeria	Almeria, Spain	4.82
SEGS	California, USA	5.86
Abengoa ISCCS project	Ain-Ben-Mathar, Morocco	4.84
Not developed	Northern Chile	~ 6

Consumption centers in the northern part of the country are mostly industrial and mining activities. These consume the highest share of power generation and plan to increase their annual production and consequently their energy requirements in future years (CNE 2006). Also, the region's has a low population density with a maximum of 25 hab/km² (INE 2005) with ample plains and flat terrains availability.

Therefore, all basic conditions for the development of CSP are met in Chile's northern region: high levels of direct solar radiation during most of the year, availability of adequate lands, and proximity to consumption centers (Price 2002). CSP is an interesting alternative for Chile to incorporate renewable energy technologies in the electrical matrix once the best locations for implementation of these plants are determined. Selection analysis must be performed for a specific plant design; therefore, best CSP plant configuration must be selected among all available solar thermal energy conversion technologies, described in the next section.

1.3 Summary

Taking into consideration environmental and depletion issues of the consumption of fossil fuels, finding adequate substitutes to reduce environmental impacts and satisfying

energy demand of future generations have become an important objective. New energy substitutes must ensure resource conservation according with sustainable development characteristics to sustain civilization's development. Then, the effective potential of a power plant for energy production must be analyzed before implementation to ensure that energy obtained from the new system must be at least equal to its life cycle energy requirement guaranteeing that the same (or more) energy invested today is going to be also available for future generations.

A solar energy generation system is an attractive alternative in northern Chile mainly because it offers elevated levels of solar radiation on most days of the year. Effectively, this solar radiation level is higher than in other locations where CSP is already in use. To account for effective energy production of this alternative installed in northern Chile and to define the best location for sitting those plants from an energy point of view it is proposed to perform an NEA for the plant lifecycle. To execute this analysis, the most convenient CSP plant configuration must be selected among all available solar thermal energy conversion technologies, described in the following section.

2. CONCENTRATED SOLAR POWER TECHNOLOGIES

Various technologies for solar thermal power generation have been studied in the last two decades. All of them make use of concentrated solar principles and most developed are central receiver, parabolic trough collectors, and Stirling-dish systems.

2.1 Concentrated solar power principles

The operation principle is the concentration of direct solar radiation in order to increase the thermal energy of a heat transfer fluid (HTF). CSP energy conversion technologies utilize concentration of the solar flux to reach higher working temperatures of the HTF and consequently higher conversion efficiencies. Each technology design has a particular concentration ratio, which is geometrically defined as the ratio between the aperture area of the collector and the receiver area (Duffie and Beckmann, 2006).

$$C = C_{geom} = \frac{A_{aperture}}{A_{receiver}} \quad (2.1)$$

To obtain a perfect concentration, parabolic geometries with linear and point focusing are used, and solar tracking is required. Solar tracking can be in one or two axes, with a central control system or a decentralized system, using individual photovoltaic sensors. Point focus has higher concentration ratios but requires 2D solar tracking, which is more expensive and difficult to control.

Solar energy is absorbed by the HTF. Different HTFs has been tested, each of them with a particular penetration ratio which describes its thermal properties. Synthetic thermal oil was the first HTF used, but it presents thermal instability problems, limit higher working temperature of 400°C and the need of complex components due to the necessity to maintain a pressurized system (Kaltschmitt et al, 2007). Molten salts appears to be a more economic option, with higher heat capacity and working temperature, but exhibits environmental and safety issues related to leakages of the fluid to the ambient (Kearney et al, 2003). Water as HTF with direct steam generation (DSG) is also used, with lower

costs and heat transfer losses as no heat exchanger system is required. Problems related to evaporation in horizontal tubes are resolved with recirculation systems and water injection (Eck and Steinmann, 2002). For other applications (like Stirling dish) air is used, with the possibility of hybrid generation, adding a backup system.

As solar radiation has intensity variations due to earth rotation (day and night) and meteorological influences, thermal energy storage and backup systems (using fossil fuels) are used to increase the number of hours of energy generation, allowing the use of the plant even during cloudy days (Price et al, 2002). Thermal energy storage configuration is directly related with the HTF and can be classified by storage mechanisms and by media (Herrmann and Kearney, 2002). Storage mechanisms are:

- Sensible heat storage: stores energy by increasing the temperature of a solid or liquid,
- Latent heat storage: stores energy using the phase transition heat, and
- Chemical storage: stores energy as chemical energy.

For thermal storage, solid and liquid media is used. Solid media is generally made of packed beds, requiring a fluid to exchange heat from and to the media. If exchange fluid has a low heat capacity, such as air, the solid is the only storage material, but for high fluid heat capacities (like liquid) the system is described as a dual storage system. Typical solid storage media are reinforced concrete, solid NaCl, cast iron, cast steel, silica fire bricks or magnesia fire bricks among others. If the media is a liquid form, thermal stratification (due to density differences) is developed in the storage tank, and mixing must be avoided. Synthetic oil, silicone oil, nitrite salts, nitrate salts, carbonate salts and liquid sodium are used as liquid media (Herrmann and Kearney, 2002).

2.2 Concentrated solar power technologies overview

Most developed CSP technologies are central receiver, parabolic trough collectors (PTC), and Stirling-dish systems. There are many variations of each basic configuration, combining different HTF and thermal storage systems, with or without backup systems.

Parabolic trough systems use a parabolic collector, which redirects solar radiation to a linear focus where the receiver is located (Price and Kearney, 1999). Through the receiver circulates the HTF which is heated. A variation of this system is the Fresnel collector, an extension of the parabola in the plane, composed by various reflective sections, located in the plane with different angles. Principal problem of this option is the complex solar tracking system required (Kaltschmitt et al, 2007).



Figure 2-1: Andasol 1 PTC Plant in spring 2008 (from Solar Millennium webpage).

Central receiver is composed of a tower (with a receiver in its upper section) and a field of heliostats. Heliostats reflect solar radiation to the receiver, and are composed by a reflective surface, motorized tracking system, support system and a control system.

Central receiver and parabolic trough systems heat a HTF, which then transfers its thermal energy to a traditional Rankine steam cycle (Goswami, Kreith and Kreider . 2004, Duffie and Beckmann 2006). In this way, these solar thermal power plants can be

thought as a traditional thermal power plant, where the heat addition from fossil fuels in the boiler is replaced partially or totally by solar heat. Unlike these plants, stirling dish system is based on the stirling cycle, which uses air (or other gas) as a working fluid and generates mechanical energy when the fluid is heated (by the sun or with a natural gas burner as a backup system).



Figure 2-2: PS10 and PS20 central receiver plant (from Abengoa Solar webpage).

Solar electric generating systems (SEGS) was the first CSP developed for commercial application, with a 13.8 MW capacity parabolic trough collector system, installed in the Mohave desert in Nevada, USA. Since then, eight new plants were integrated to this facility, reaching a 354 MW of capacity installed.

First demonstration of the Central receiver technology was Solar ONE 10 MW plant, also installed in the Mohave desert and in operation between 1982 and 1988. HTF of this plant was water, and no thermal storage was used. This plant was reconstructed as Solar TWO, which operate with molten salt as a HTF and includes thermal tank storage, extending electricity production for 3 hours. Phoebus/TSA/Solair experimental system at

the Plataforma Solar de Almería, Spain, include hybrid operation with air as HTF. The first commercial central receiver plant, with a capacity of 10 MW called PS10 was constructed in Spain and started operation in 2007. This design included direct steam generation and latent heat storage. There are many others projects in operation and construction, such as Solar Tres and PS15, with higher capacities and many improvements to the basic design.

There are no operating commercial dish-Stirling power plants (Stoddard et al, 2006), and its energy generation costs are expensive compared with the other CSP technologies. The main benefit of this technology is the possibility of stand-alone operation mode without water requirements.

It has been argued that CSP is the most convenient solar energy conversion systems in economic terms, with their cost projections being such that they are becoming competitive with traditional power plants (Price, 2003, Sargent and Lundy 2003).

2.3 Selection of the most convenient alternative for Chile

Within CSP technologies, parabolic trough collectors system is the most developed (Stoddard et al, 2006) in commercial operation since 1985 and have the lowest energy generation cost of approximately 0.12 €/kWh (Kaltschmitt, 2007). Then, this technology is the most convenient alternative for electricity generation in grid operation as shown in Table 2-1, considering its development status and energy generation costs. In view of this, this technology has been selected for this study, to analyze the performance of a hybrid solar power plant in north Chile and perform a NEA of it lifecycle.

An important advantage of selecting the PTC technology to perform the NEA analysis is that there is a high quality and quantity of specific available data about its components and processes in comparison with the other alternatives. A more accurate NEA can be performed when more information of the analyzed process is available.

In the next section, a more detailed description of the PTC power plant development and different configurations is presented.

Table 2-1: Comparison of CSP technologies (from Kaltschmitt, 2007)

CSP Technology	Solar Tower	Stirling Dish	Parabolic Trough collector
Typical capacity MW	30-200	0.01-1	10-200
Concentration ratio	600-1000	>3000	50-90
Efficiency %	10-28	15-25	10-23
Operation mode	grid	grid/island	grid
Electricity generation cost €/kWh	0.13	0.23	0.12
Development status	+	+	++

2.4 Parabolic trough collector power plants

As explained before, from CSP technologies, the parabolic trough collector power plant is the most developed and proved, with commercial use in the US since 1982 with new plants being built in Spain, USA, Morocco, Algeria, India and Iran (Eichhammer et al, 2005; Price and Kearney, 1999). Today, a few companies are interested in developing and implement CSP projects, i.e. Abengoa Solar, Solel, Solar millennium AG and Acciona among others, with a total world installed PTC capacity reaching more than 400MW, and a projected growth to almost 600 MW by 2010 (Price and Kearney, 1999).

The PTC concept is simple, and basically focuses direct solar radiation in an absorber tube, which is located at the center of an evacuated glass tube for minimizing thermal losses. The concentration factor for this kind of plant is near 90 (Duffie and Beckmann 2006), and the system can be as large as required by using a modular configuration like

in the SEGS plants, where total capacity is obtained with a combination of 30 and 80 MW power plants (Solel webpage, 2008). As the technology uses a linear focus working temperature is lower than for the central receiver or the Stirling Dish system. Land requirement for the plant is high of compared with traditional generation plants with approximately 1 km² for each 50 MW installed (Broesamle et al, 2001). This is an environmental issue nevertheless frequently solar plants are typically located in desert regions with low population and alternative terrain use minimizing the impact. In the Atacama desert, alternative terrain use can be related to the mining industry. Unfortunately, there are a small number of locations with this potential.



Figure 2-3: Parabolic trough in PSA, Almería.

PTC plants have two principal components: the solar field and the power generation system. Solar field is an array of PTC formed by a collector, an absorber and a solar tracking system.

2.4.1 Solar field properties

Solar field is a PTC array formed by a number of collectors loops connected in one side to a feeder line called “cold header” and to the other side to a discharge line called “hot header”. Considering a system with a high number of collector rows, shading between collectors is an important issue to consider in solar field design. Row distance is optimized as a function of the collector dimensions. A north-south alignment is used to minimize shading loss.

2.4.2 Parabolic trough collector

The parabolic trough collector is composed by the collector surface, absorber and a sun tracking system. The collector’s surface redirects solar radiation to the absorber with thermal and optical losses between 40 and 70%, depending on collector design, size and plant location. Two different designs of collectors have been developed (Kaltschmitt, 2007):

- Parabolic trough collector: characterized by a parabolic reflective surface which is a thin film of metal foil or glass mirror or an aligned array of curved mirrors assembled in a supporting structure. One collector assembly (of approximately 100 m) is composed by a number of collector elements with an aperture near 6 m. The collector is mounted on a tracking structure equipped with a tracking engine.
- Fresnel collectors: parabola shape is extended on the plane by individual mirror segments which follow the sun, similar to heliostats. Due to their lower width they have no wind loads problems but present lower efficiencies and require a more complex tracking system.

Absorber (also called heat collector element, HCE) is a horizontal tube located in the parabola focus. For Fresnel collectors, with a wider image, absorber may be an arrangement of tubes. Usually the absorber is a stainless steel tube with a selective coating covered by a glass envelope to minimize heat losses. As seen in Figure 2-4, vacuum between glass and the metal tube is applied to reduce thermal losses.

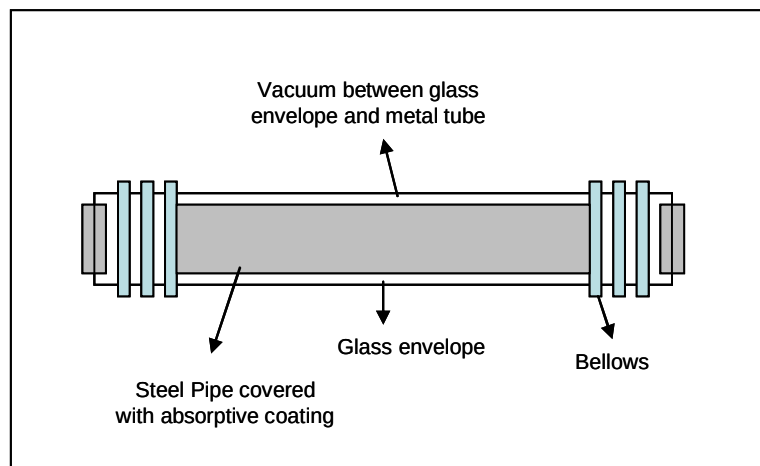


Figure 2-4: Absorber of a parabolic trough collector.

2.4.3 Power generation system of a PTC plant

There are two basic configurations for PTC plants as a function of the working fluid. The first is direct steam generation where only water is the HTF, and the second is a two working fluid concept with molten salt or synthetic oil as the HTF heated by the solar field which then transfers the thermal energy to a Rankine cycle in a heat exchanger. As displayed in Figure 2-5, both configurations utilize Rankine cycle to produce mechanical energy.

As shown in the figure DSG system has a simpler plant configuration which implies a fewer number of components with the possibility of cost reduction. A generator added

to the turbine transforms mechanical energy in electricity. Many variations to these basic configurations can be made. An additional fossil-fired boiler can supply back-up heat during night or can stabilize the steam properties in order to maintain a constant power output for cloudy days. Given sufficient solar input the plant can operate at full rated power using solar energy alone. During summer months the plants typically operate for 10-12 hrs/day on solar energy at full rated electric output (Price et al 2002). Use of backup systems has been limited in developed countries in an attempt to reduce the environmental impact derived from fossil fuels consumption. In Spain, maximum backup fraction allowed by law is 25%. In other countries such as Chile, incentives or legislation to reduce GHG emissions do not exist. Then, backup fraction in Chile can be as high as wanted with the possibility to develop a hybrid power plant, combining solar energy with the traditional fossil fuels power plants, in order to initiate incorporation of renewables to the country electricity's generation matrix. Most solar power plants in operation today also integrate thermal energy storage to extend operation 4-6 hours after sunset. These both technologies ensure the supply of energy at any time it is required.

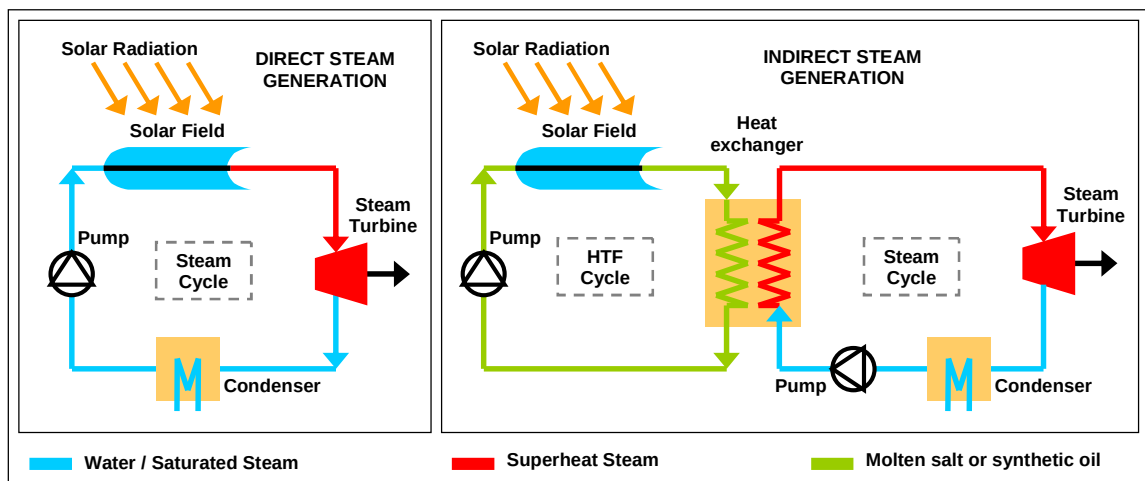


Figure 2-5: Two basic designs for PTC.

Other improvements to CSP are being research study for future installations. Direct steam generation reduces heat exchanger losses (Almanza et al, 1997; Eck and Steinmann, 2002; Eck et al, 2003) and new configurations like integrated solar combined cycle system (ISCCS) increase cycle efficiency including gas turbine generation reducing electricity generation costs (Price and Kearney, 1999). It can be distinguish different configurations used today:

- CSP with HTF and energy storage (used in SEGS I)
- CSP with back-up (fired boiler, used in SEGS II-VII)
- CSP with back-up (fired HTF heater, used in SEGS VIII-IX)
- DSG systems
- ISCCS: Projects in construction by Abengoa: 155MW Plant at Hassi-R'mel, North Africa and 450MW Plant at Ain Beni Mathar (Abengoa webpage, 2008)

Commercial systems have demonstrated that the concept works and the technology is readily available for commercial users. In this regard, a learning curve has been developed, which has reduced the electricity generation costs (Sargent and Lundy, 2003). Most of the research is being focused on achieving higher plant availability and efficiency by means of energy storage, improvement of the HTFs, better prediction of available solar radiation, and direct steam generation techniques (Price et al., 2002, Duffie and Beckmann, 2006, Zarza et al, 2006).

2.5 Parabolic trough collector power plants history and development

PTC plants found several barriers to their deployment in the 70's and 80's. The principal barrier was the worldwide fossil fuel energy price instability that affected the competitiveness of PTC plants (Price et al 2002, Klaib et al 1995, Trieb et al 1997). Conditions have changed since then and PTC plants are more competitive in the actual context of processes with high energy use and environmental pressures (Trieb 2000, Kalogirou 2002, Tsoutsos et al 2003, Sargent and Lundy 2003, Mills 2004). As a

consequence efforts has been devoted to the development of adequate steps for cost reduction that defined several research priorities with an estimated cost reduction potential of up to 40% (Pitz-Paal et al., 2007). Improved assessment of solar energy resources is perceived to be the first step in developing a technical program that will lead to proper installation of CSP plants that are economically feasible. An erroneous input for direct solar radiation can lead to an erroneous size of collector field that will result in severe financial difficulties for the plant during operation. In this context, computational simulation is perceived as the best tool for properly estimating collector field size during the design stages of PTC plant planning (Quasching et al, 2002).

2.6 Summary

As presented in this chapter solar thermal power generation technologies make use of concentration to obtain higher working temperatures and reach higher efficiencies. Also, hybridization and heat storage has been developed to increase plant load factor. The most developed CSP's are central receiver, parabolic trough collectors, and Stirling-dish systems and in commercial applications trough collectors systems is considered the most convenient alternative for electricity generation. This is considering its development status and power generation costs.

Then, PTC technology has been selected in the present study to perform the NEA considering that it can display a better performance than other CSP alternatives. In the following chapters, procedures to achieve NEA of the parabolic trough collector plant in north Chile are explained, and results of the analysis presented.

3. THESIS OBJECTIVES

Since the industrial revolution global energy demand has grown in support of the world's development. In Chile, energy consumption has also presented a large expansion over the years and is expected to maintain its tendency in order to ensure the country's development requirements. Chilean energy demand is satisfied mainly by fossil fuels utilization that carries several issues related with the dependence on foreign imports and worldwide fuel availability and price. Additional problems to fossil fuels use are the depletion of the resources and GHG emissions that speed up climatic change. For Chile this represents a transcendental challenge which is to develop a transition strategy and to replace fossil fuels as the major energy source, in order to reduce GHG emissions and environmental consequences, decrease energy dependence from foreign countries and guarantee energy availability to ensure the country's development. New energy generation technologies must satisfy sustainable development, take care of resource depletion, and most importantly ensure that energy obtained from the new system must be at least equal to his life cycle energy requirement guarantying that the same (or more) energy invested today is going to be also available for future generations. As CSP is an interesting alternative within renewables for Chile it must be demonstrated that CSP plants in north Chile meets these requirements. Since solar radiation levels vary through the country, some locations will become more convenient in energy terms than others for the installation of the plant.

The general objective of this work is to propose a selection methodology to determine optimal plant location based in the net energy analysis and energy sustainability indicators. Those indicators will provide additional data to support the decision making process related to the placement of CSP plants in Chile considering that the location where CSP plants are installed determines lifecycle net energy production.

To perform the NEA of the plant, substantial specific information is required related to the plant properties and processes, the solar radiation of the specific locations, and total

fossil fired backup required during the plant's lifecycle. A performance model of the plant is essential to obtaining plant backup requirement.

The specific objectives of this study are broken down in two stages of development: pre analysis objectives and analysis objectives. Pre analysis is related with data compilation and preparation and with model specification. Specific objectives of this stage of the investigation are:

- Investigate CSP technologies and selection of the one with the best prospects to be developed in Chile.
- Collection of sufficient data to analyze plant configuration and to perform the NEA of the plant lifecycle.
- Conversion of solar global radiation data for each location into direct radiation data to be used as an input in the plant model, considering that CSP technologies only make use of direct radiation to generate energy.
- Selection of suitable locations to be analyzed, in north Chile Atacama desert, considering PTC plant terrain requirements.
- Setting system boundary.
- Selection of the plant configuration to be analyzed.

Second stage of the investigation is related with the plant model, energy accounting and results of the net energy analysis. Specific objectives are:

- Develop a thermodynamic model of the plant in order to quantify annual electricity production and backup fraction required for each location analyzed.
- Quantify life cycle energy requirements of the plant.
- Perform a NEA of the plant, and determine energy input and outputs for each location.

- Investigate energy attributes (net energy, energy return over investment and energy payback time) of PTC installed in the Atacama Desert.
- Identify high energy-consuming processes within the systems lifecycle, in order to analyze process replacement or improvement possibility.
- Analyze results and propose best locations where best energy attributes and sustainability of the plant are achieved.

It is expected that results from the thermodynamic model of the plant will show that for each plant location, with its respective solar radiation values, different backup requirements will be required.

As a specific result it is expected to demonstrate that PTC power plants in north Chile are net energy positive while demonstrating that the technology is not only a solution to reduce GHG emissions but that it also represents an alternative as an energy source without compromising energy resource depletion thus ensuring resources to future generations.

An additional result is to prove that for higher backup fractions lower net energy and energy return over invested (EROI) are obtained, considering the high energy requirement for fossil fuel extraction and production while demonstrating that energy requirement related with fossil fuels lifecycle is the most important component in total plant lifecycle energy requirement.

Regarding data of EROI results for other traditional energy generating systems it is expected that a parabolic trough collector power plant with natural gas backup present the best result comparable to a typical natural gas power plant.

By doing the analysis the NEA proposed methodology can be validated as a selection tool in addition to economic or environmental analyses for determining under which conditions not only CSP plants but all energy generation technologies becomes a net

energy source and a more convenient option to consider them as a renewable energy source.

Finally, it is expected that the present work would open a discussion about the importance of analyzing the effects of actual decisions on energy resource depletion in order to ensure energy resource availability to future generations and achieve a sustainable development. Then, it is recommended to incorporate the net energy analysis for each new evaluation project as a complement to the environmental and economic analysis.

4. BEAM SOLAR RADIATION ESTIMATES

It is important to keep in mind that CSP technology uses mirrors to concentrate radiation and only beam radiation is reflected into the absorber element. Then, beam solar radiation must be obtained from global radiation data to model the performance of the plant. First step is to determine the locations to be analyzed and then to obtain solar radiation data for each of them.

4.1 Selected locations

Different latitude locations were selected in northern Chile to analyze PTC plant performance. Appropriate location to install a PTC plant has to meet specific requirements according to plant design. Because this kind of plant needs large use of terrain any inclination of the plant must be minimized to reduce costs by choosing terrains with ground inclination lower than 1%. One other important point to consider is proximity to mining clusters or industrial consumption centers that may require energy supply increases during the future. Additional factors to be considered are proximity to harbors and access to roads. As displayed in the Figure 4-1 four locations are homogeneously spread in the north of the country. The selected points are located within a narrow longitude band between 70°W and 70.5°W, with latitudes between 19°S and 31°S, as shown in Table 4-1. All of them are located in the Atacama Desert region.

Table 4-1: Latitude and longitude for each location

Location	Latitude	Longitude
1	19.08	69.93
2	22.32	69.33
3	27.83	70.53
4	30.23	71.40



Figure 4-1: Map with selected locations in northern Chile.

4.2 Monthly average daily radiation available at selected locations

The satellite estimations of monthly average global solar radiation for each location obtained from Ortega, Escobar and Colle (2008) are shown in Figure 4-2. As can be seen, the solar radiation peaks during summertime at values close to $7 \text{ kWh/m}^2\text{-day}$ with a minimum nearing $3 \text{ kWh/m}^2\text{-day}$ in winter. These values are equal or better than those

registered at some locations in Spain, USA and Morocco where operative CSP projects exist (see Table 1-1).

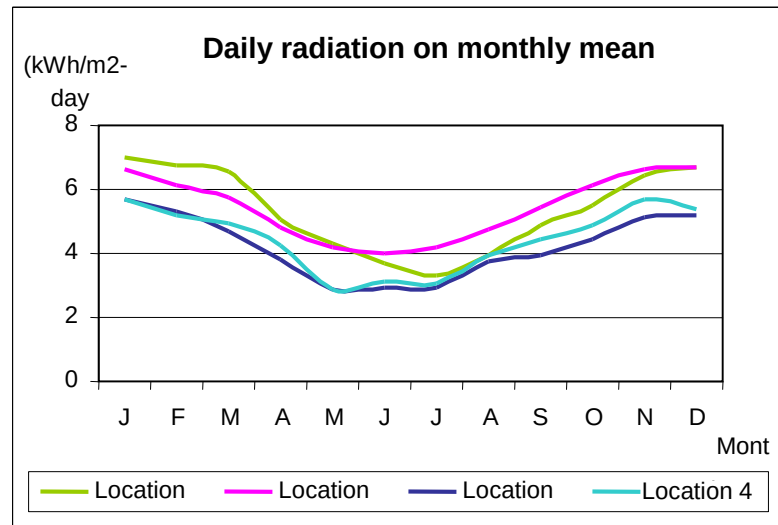


Figure 4-2: Daily radiation on monthly mean at selected locations.

A model of the plant performance can be obtained using monthly mean data of solar radiation considering that each day of the month is equal to the average day, but as explained in the next section, using the utilizability concept, more accurate results may be obtained when a model with daily data is performed.

4.3 Utilizability for a parabolic trough collector

For a specific solar collector design only radiation over a critical level of intensity is useful. This Critical radiation level (I_c) is defined as the level at which energy absorbed in the collector becomes higher than its thermal losses. The fraction of beam radiation I_b above I_c is called utilizability (ϕ_h).

$$\phi_h = \frac{I_b - I_c}{I_b} \quad (4.1)$$

And a dimensionless critical radiation level is defined as:

$$X_c = \frac{I_c}{I_b} \quad (4.2)$$

For a specific month, cumulative distribution curve for hourly beam radiation over average hourly beam radiation ($I_b / \bar{I}_b$) can be obtained, as shown in Fig. 4-3, evaluating $I_b / \bar{I}_b$ for each day of the month and graphing its values in an upward order and considering fractional time f for each day of the month as the day over the total days in the month.

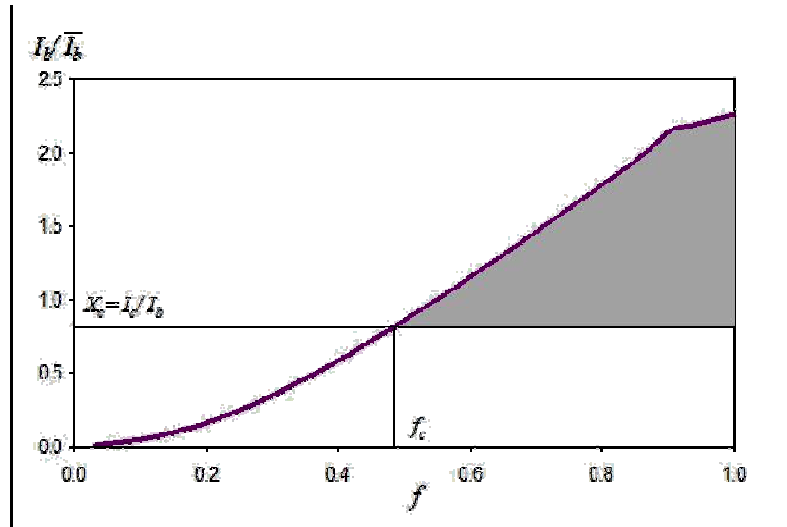


Figure 4-3: Cumulative distribution curve for hourly beam radiation over average hourly beam radiation, for Latitude 19.08 South, in February, for the hour pair 10 to11.

For example, in upward order, value number 12 for a 30 days month has a fractional time of 12/30 or 0.4, which means that 40% of the days of the month have a $I_b / \bar{I}_b$

value lower than value number 12. For a given critical radiation level monthly utilizability is represented as the shaded area in the figure and that can be obtained integrating hourly utilizability over all values of f_c .

$$\phi = \int_{f_c}^1 \phi_h df \quad (4.3)$$

If radiation data for each day of the month is not available, a month with identical days in which every day looks like the average day can be used. The main problem with this assumption is that utilizability for an all identical days month is lower than for the real month, as shown in Fig. 4-4. If the collector field size is determined using this approach, an oversize field is expected with unnecessary higher costs of construction and installation as a consequence.

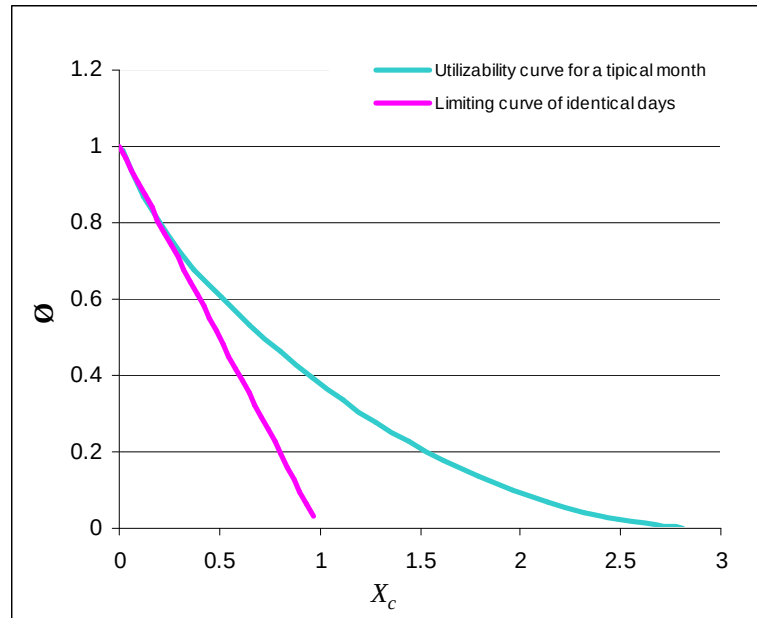


Figure 4-4: Cumulative distribution curve for hourly beam radiation over average hourly beam radiation for Latitude 19.08 South, in February, for the hour pair 10 to 11.

Then, it is necessary to fabricate an “artificial month” from monthly mean radiation data to obtain a better estimation of energy gain in the collector field and the required backup.

4.4 Estimation of daily radiation from monthly average

Data of Chilean Solar Radiation from Ortega, Escobar and Colle (2008) are in monthly average of daily total radiation ($\bar{H}$ for each location). With this data, it is possible to fabricate an artificial month (Duffie and Beckmann, 2006), obtaining an artificial daily total radiation value H for each day of the month.

A particular monthly average clearness index $\bar{K}_T$ is defined for each month as:

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_o} \quad (4.4)$$

Where $\bar{H}$ is obtained from the satellite estimations (Ortega, Escobar and Colle, 2008), and $\bar{H}_o$ is the monthly average extraterrestrial radiation, which is computed for each location as function of its latitude. Then, the frequency of occurrence of days with a value of the clearness index K_T have a special distribution, and the fraction f of the days in the month that are less clear than K_T is define with Bendt et al. correlation as function of $\bar{K}_T$:

$$f(K_T) = \frac{\exp(\gamma K_{T,\min}) - \exp(\gamma K_T)}{\exp(\gamma K_{T,\min}) - \exp(\gamma K_{T,\max})} \quad (4.5)$$

Where:

$$\gamma = -1.498 + \frac{1.184\xi - 27.182 \exp(-1.5\xi)}{K_{T,\max} - K_{T,\min}} \quad (4.6)$$

$$\xi = \frac{K_{T,\max} - K_{T,\min}}{K_{T,\max} - \bar{K}_T} \quad (4.7)$$

$$K_{T,\min} = 0.05 \quad (4.8)$$

$$K_{T,\max} = 0.6313 + 0.267 \bar{K}_T - 11.9 \cdot (\bar{K}_T - 0.75)^8 \quad (4.5)$$

Using the Engineering Equation Solver (EES) program these equations are solved for each month obtaining artificial H for each day. As seen in Fig. 4-5 and 4-6 days in the artificial month are arranged from the lowest to the highest H . The order of the days does not affect simulation results.

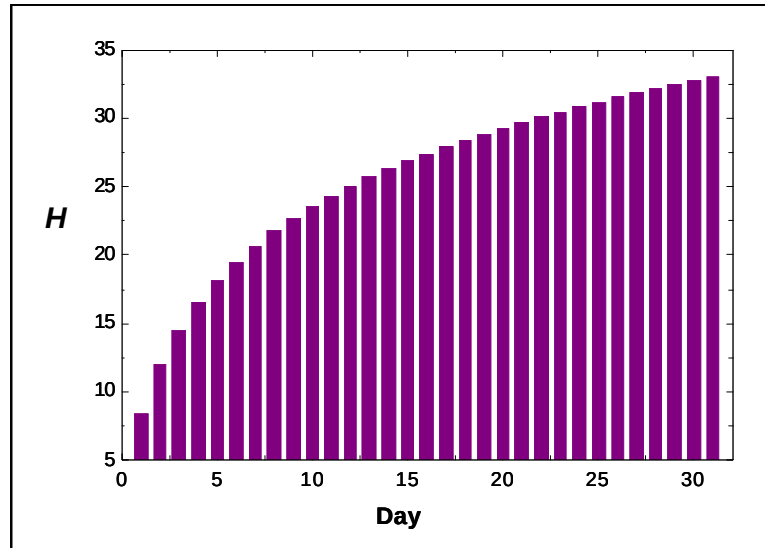


Figure 4-5: H for January, based on $\bar{H} = 25.2 \text{ MJ} / \text{m}^2 \text{ day}$ for Location 1.

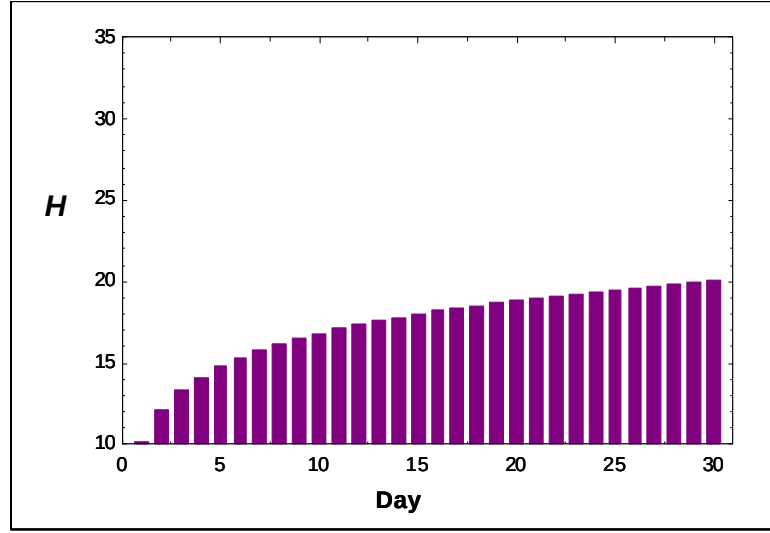


Figure 4-6: H for June, based on $\bar{H} = 17.1 \text{ MJ} / \text{m}^2 \text{ day}$ for Location 1.

4.5 Estimation of beam component of daily radiation

The daily total beam Radiation H_d for the selected locations can be obtained from correlations (Duffie and Beckmann, 2006) as function of the daily clearness index that is defined as:

$$K_T = \frac{H}{H_o} \quad (4.6)$$

The correlation from Erbs is then used to define the daily total diffuse fraction for sunrise hour angle $\omega_s \leq 81.4^\circ$ as:

$$\frac{H_d}{H} = \begin{cases} 1 - 0.2727 K_T + 2.4495 K_T^2 - 11.951 K_T^3 + 9.3879 K_T^4 & \text{for } K_T < 0.715 \\ 0.143 & \text{for } K_T \geq 0.715 \end{cases} \quad (4.7)$$

And for $\omega_s > 81.4^\circ$

$$\frac{H_d}{H} = \begin{cases} 1 + 0.2832 K_T - 2.5557 K_T^2 + 0.8448 K_T^3 & \text{for } K_T < 0.715 \\ 0.175 & \text{for } K_T \geq 0.715 \end{cases} \quad (4.8)$$

Then, the daily diffuse radiation is computed and the daily beam radiation H_b is simply:

$$H_b = H - H_d \quad (4.9)$$

As shown in figures 4-7 to 4-10, H_b for the selected locations is approximately 70% of global horizontal radiation.

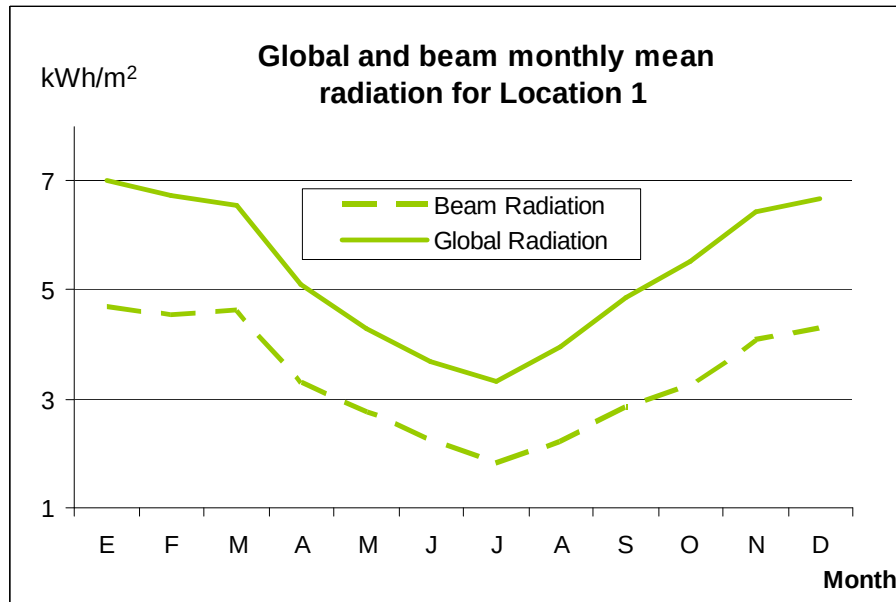


Figure 4-7: Global $\bar{H}$ and beam $\bar{H}_b$ monthly mean radiation at location 1.

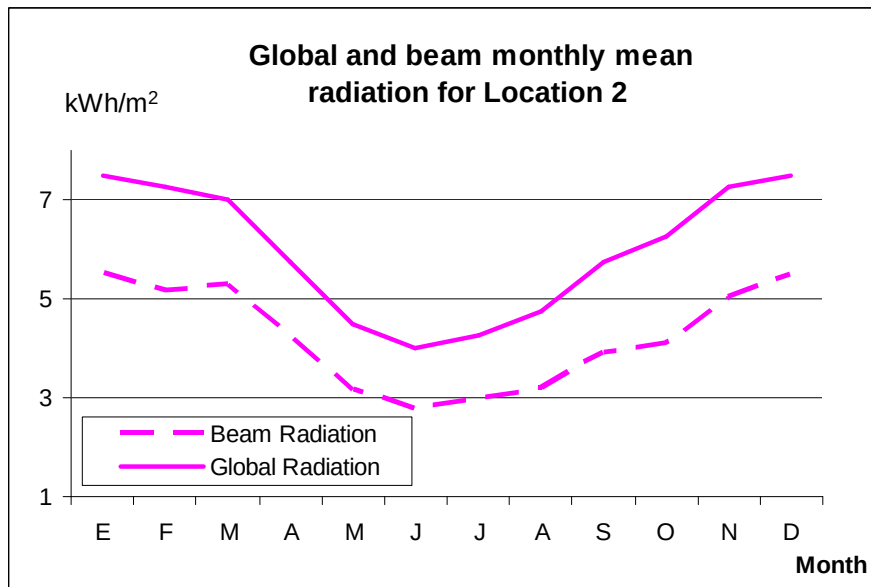


Figure 4-8: Global $\bar{H}$ and beam $\bar{H}_b$ monthly mean radiation at location 2.

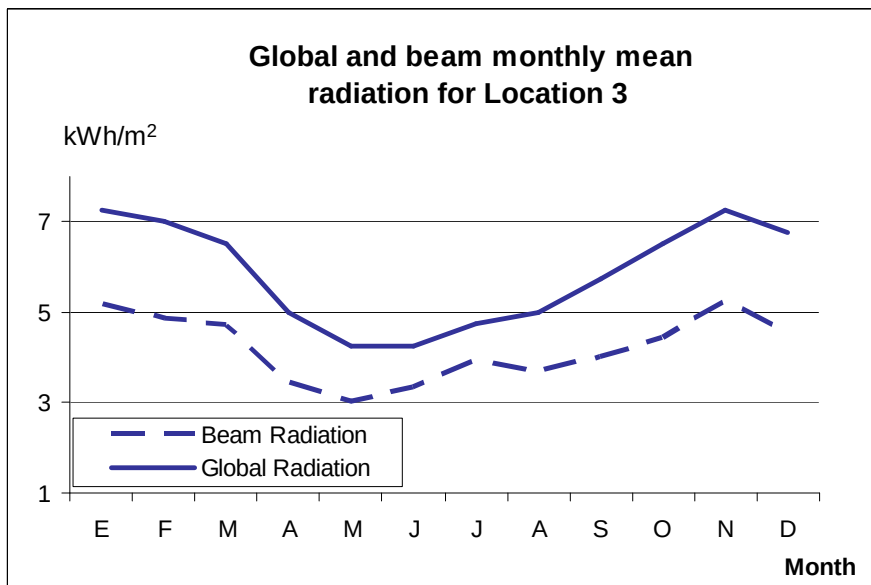


Figure 4-9: Global $\bar{H}$ and beam $\bar{H}_b$ monthly mean radiation at location 3.

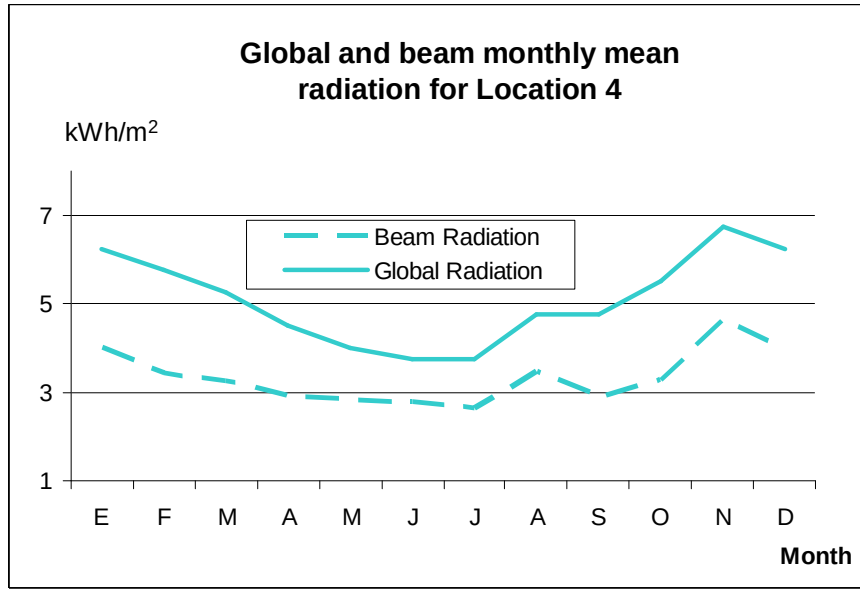


Figure 4-10: Global $\bar{H}$ and beam $\bar{H}_b$ monthly mean radiation at location 4.

A simplified analysis of the plant using total beam radiation H_d for the selected locations can be achieved as a first approximation to obtain PTC power plant performance, but modeling using hourly data can provide more accurate results. Then, hourly radiation must be estimated.

4.6 Estimation of hourly radiation I from daily data

Then, with H for each day of the year, hourly radiation I is obtained from the ratio of hourly total to daily total radiation r_t , as a function of day length, the hour in question (as hour angle ω) and the sunset hour angle ω_s :

$$r_t = \frac{I}{H} = \frac{\pi}{24} \cdot (a + b \cdot \cos(\omega)) \cdot \frac{(\cos(\omega) - \cos(\omega_s))}{\left(\sin(\omega_s) - \frac{\pi \cdot \omega_s}{180} \cdot \cos(\omega_s) \right)} \quad (4.10)$$

$$a = 0.409 + 0.5016 \cdot \sin(\omega_s - 60) \quad (4.11)$$

$$b = 0.6609 - 0.4767 \cdot \sin(\omega_s - 60) \quad (4.12)$$

Similarly, hourly diffuse radiation I_d is obtained with the ratio of hourly beam to daily beam radiation r_d :

$$r_d = \frac{I_d}{H_d} = \frac{\pi}{24} \cdot \frac{(\cos(\omega) - \cos(\omega_s))}{\left(\sin(\omega_s) - \frac{\pi \cdot \omega_s}{180} \cdot \cos(\omega_s) \right)} \quad (4.13)$$

With hourly total radiation and hourly diffuse radiation values, hourly beam radiation I_b is simply obtained from equation 4.13.

$$I_b = I - I_d \quad (4.13)$$

Hourly total and hourly beam radiation distribution for any day of the year could be estimated by this method (as displayed in figures 7.1 and 7.2) and these values can be used as an input to obtain solar field performance.

4.7 Summary

As PTC can only exploit beam radiation it must be derived from global radiation available data (Ortega, Escobar and Colle 2008). To obtain PTC plant performance, a model which requires hourly beam radiation for each hour of the year as an input is developed (see model details in chapter 5). Hourly beam radiation data can be estimated from daily total radiation H for each day of the month. To obtain daily radiation from monthly means two alternatives can be used: first, consider a month with identical days, in which every day looks like the average day; and second an artificial month can be fabricated using monthly mean data. From an utilizability point of view the first alternative provides sub estimations of utilizable energy. Then, it is recommended to use

it only to perform approximations or pre evaluations. To obtain more accurate results an artificial month can be fabricated.

Hourly beam radiation data for each hour of the year is finally obtained to be used as an input to the solar field model and obtain backup yearly requirement of the plant. In the next chapter a model of the plant will be proposed for this purpose.

5. MODELING OF THE PTC HYBRID PLANT

A 100 MW hybrid power plant of concentrated solar power is selected for evaluation considering the use of a natural gas backup system to maintain a continuous operation. Backup of the plant is one of the most important components in the NEA and the amount of fossil fuel required yearly is obtained when a model of the plant is performed. As defined in point 5.2 to maintain plant production at 100 MW the working fluid temperature at the turbine inlet is required to be at 410°C. In the solar field analysis, the solar field outlet fluid energy is estimated and then the backup required to reach the 410°C is calculated. Considering radiation data for northern Chile it is possible to assume that the plant operates 12 hours with solar power assisted by a fossil fuel backup system and the following 12 hours in a natural gas only generation setting. A first approximation to obtain backup estimates may be made using plant efficiencies and radiation data but a detailed analysis of the plant is required to obtain accurate values. In view of plant configuration and complexity of the system an energy balance of the plant is modeled with the EES program. Specific design of the plant must be defined before modeling of the plant.

5.1 CSP plant configuration

In order to evaluate the electricity production of a CSP plant in Chile we have selected the direct steam generation concept, mainly because DSG allows higher system efficiency, lower number of components, enhanced plant simplicity, and reduced risk of HTF leaks to the environment (Eck and Steinmann, 2002). This is an interesting alternative to basic PTC plants of the HTF type (Odeh et al., 1998, Kalogirou et al., 1996, Thomas 1996, Almanza et al. 1997). The direct solar steam (DISS) project created to evaluate DSG benefits reported a 26% decrease in electricity generation costs known by means of extensive testing of a DSG facility and use of computational simulations for the absorber tube (Eck and Steinmann, 2002, Zarza et al., 2002, Eck and Steinmann 2005) demonstrating steam conditions of 100 bar and 410°C. It was found

that a levelized electricity cost (LEC) of \$0.1/kWh was feasible, that a great potential for improvement still exists due to the simplicity of DSG schemes compared to traditional SEGS systems, and that the recirculation scheme was the most efficient of those tested (Eck et al. 2003). The final conclusions of the DISS project indicate that is totally feasible to generate steam in PTC systems with horizontal tubes, and have resulted in the INDITEP project aiming to develop a commercial DSG plant (Zarza et al. 2004). The INDITEP project finally resulted in a pre-commercial DSG solar power plant of 5 MW with steam conditions of 410°C and 65 bar. That DSG concept was tested and proven in Spain, where solar radiation is lower than in Chile implying that the results can certainly be better in Chile. Considering the Chilean market and new regulations in renewable energy, the scarcity of fossil fuels and the availability of solar resources in the region, the implementation of PTC systems is seen as an interesting opportunity for clean electricity supply.

The analysis considered a plant model described in Fig. 5-1, similar to the INDITEP plant model. The thermodynamic state at the turbine inlet and outlet are fixed in order to maintain continuous generation. Then, if the solar radiation conditions are such that the fluid needs additional heating, a fossil-fired back-up system is used (auxiliary heater in Fig. 5-1).

A total fluid mass of 142 kg/s is required to reach the desired power output at fixed conditions. This total mass must be distributed in the collector rows. Mass flow for each collector row is determined by considering the results of the DISS project in which it was concluded that liquid-water stratification due to evaporation in the collector is avoided for a mass flow above a specific limit determined for a particular working pressure (Zarza et al, 2006). A flow mass of 1.42 kg/s per row is recommended to avoid stratification at selected working pressure, and this value is used in the present study. In conclusion, 100 collector rows of with a 1.42 kg/s of mass flow each are required for a 100 MW output. The solar field modeled is composed by 10 modules each with 10 rows of collectors.

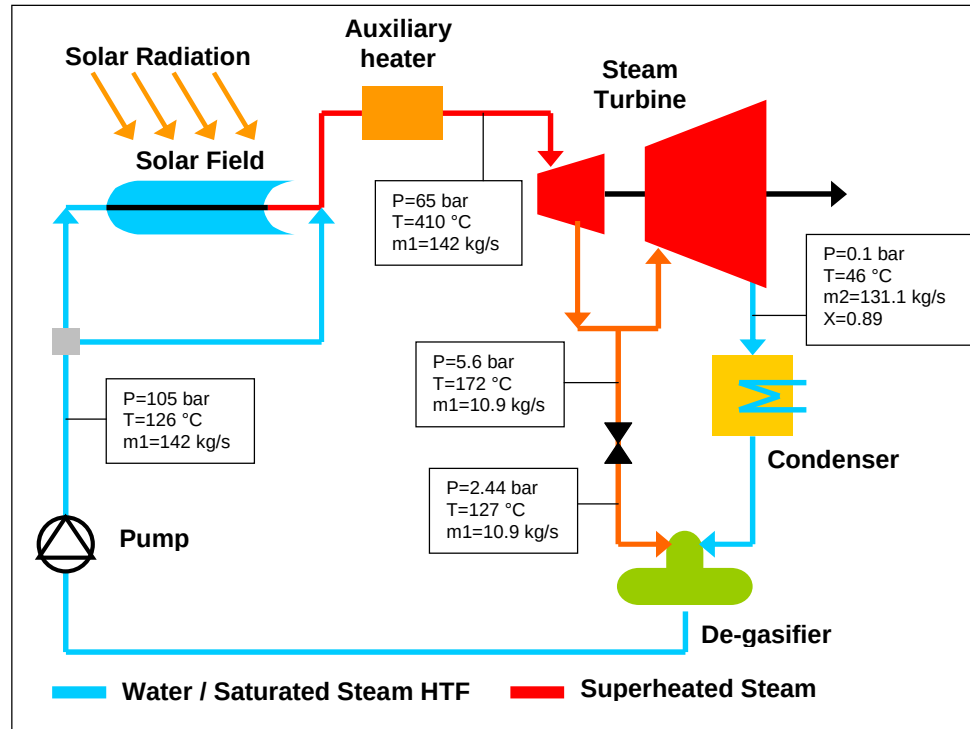


Figure 5-1: Solar DSG plant configuration with back-up system.

One row is composed by 14 ET-100 collectors as described in Table 5-1 (Zarza et al, 2006). Dimensions of one module of the solar field are shown in Figure 5-2.

Table 5-1: Properties of the ET-100 parabolic trough collector

Overall length of a single collector (m)	98.5
Parabola width (m)	5.76
Outer diameter of absorber pipe (m)	0.07
Inner diameter of absorber pipe (m)	0.055
Optical efficiency	0.733
Glass tube diameter (m)	0.115
Glass tube emissivity	0.9

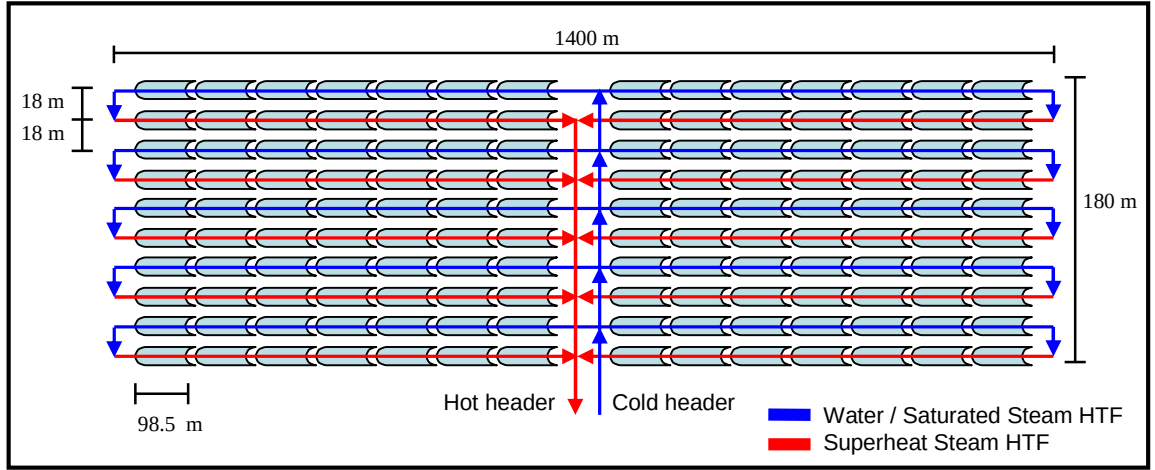


Figure 5-2: DSG plant configuration with back-up system (dimensions in meters)

Given that the solar field is configured by parallel rows of collectors, with identical characteristics, it is expected the same performance and final fluid temperatures for each row. Then, modeling of the solar field can be performed for one row, assuming that all rows are similar to the modeled one and considering a homogeneous temperature in the hot header.

5.2 First approximation to backup requirements

Before performing a model of power plant performance to obtain the backup required, it is interesting to perform a first approximation of the problem and obtain an estimated value of monthly backup to be used as a reference in the analysis. An estimation of monthly backup fraction may be obtained by using system efficiencies to calculate the total efficiency of energy transformation of the plant. Then, the fraction of the total power generated from solar radiation can be computed for each month as:

$$\dot{E}_{solar} = \eta_{sf} \cdot \eta_{sc} \cdot \eta_p \cdot \eta_a \cdot A_{sf} \cdot X_c \cdot \bar{H}_b \quad (5.1)$$

Where:

- η_{sf} is the optical efficiency of the solar field, which is approximately 37,2% (Sargent and Lundy, 2003)
- η_{sc} is the steam cycle efficiency at 38%
- η_p is the parasitic loss coefficient (approximately 95% considering an internal consumption of 5%, similar to the INDITEP model)
- η_a is the plant availability factor, which for this study is considered to reach 98%
- A_{sf} is the solar field collector area equal to 794.304 m²
- X_c dimensionless critical radiation level, assumed as 5% for a first approximation, and
- $\bar{H}_b$ monthly mean beam radiation, in W/m².

Power generation from solar energy for each location can reach a peak near 100 MW and the difference needed to maintain a uniform power generation is obtained by using the fossil fuels backup system, as

$$\dot{E}_{Backup} = 100MW - \dot{E}_{solar} \quad (5.2)$$

And the backup fraction for each month is:

$$\% \text{ back up} = \frac{\dot{E}_{backup}}{100} \quad (5.3)$$

Backup obtained by this method is used as a reference to the analysis. Also, considering the simplicity of this first approach it is expected that obtained values would be an over estimation of real values.

5.3 Solar field analysis: collector energy balance

Total energy needed to reach temperature of the working fluid to 410°C is obtained with fluid properties at pump outlet and turbine inlet:

$$\dot{Q}_{tot} = \dot{m} \cdot (h_{out,pump} - h_{in,turbine}) \quad (5.4)$$

Part of this total energy is added to the working fluid at the solar field, and the rest of the energy required to reach working temperature is added at the backup system. As explained in detail in section 5.1, working fluid properties at each point of the thermodynamic cycle are fixed and known, except for properties at solar field outlet (and backup system inlet), which means that how much energy is added by each system is unknown. It depends on solar radiation levels and solar field performance, which means fluid properties at these points are dynamic. By modeling solar field performance, properties at the point between solar field outlet and backup system inlet may be obtained, and additional energy required to reach turbine inlet fluid properties (backup requirement) can be computed.

Same characteristics, performance and final fluid temperatures for each row of collectors are assumed. Then, modeling of the solar field is performed for one row, assuming that all rows are similar to the modeled one and considering homogeneous temperatures in the hot header. To model one collector's row it is assumed that each row is a single collector with greater length. Then an energy balance for each segment of the collector is required using inlet properties to obtain outlet properties for each segment.

Working fluid energy gain, $\dot{Q}_{fluid}$ when fluid circulates through the collector for an energy loss $\dot{Q}_L$ is obtained from the energy balance:

$$\dot{Q}_{fluid} = \dot{Q}_{abs} - \dot{Q}_L \quad (5.5)$$

$\dot{Q}_{abs}$ is absorbed radiation for a collector with aperture a and length L :

$$\dot{Q}_{abs} = \rho \cdot (\gamma\tau\alpha)_n \cdot K_{\gamma\tau\alpha} \cdot a \cdot L \cdot I_{bT} \quad (5.6)$$

With:

- ρ : Specular reflectance (diffuse reflectance) of the concentrator,
- γ : intercept factor,
- τ : transmittance of the receiver cover,
- α : absorptance of the absorber, and
- $K_{\gamma\tau\alpha}$: incidence angle modifier.

These terms characterize collector efficiency (η_{coll}):

$$\eta_{coll} = \rho \cdot (\gamma\tau\alpha)_n \cdot K_{\gamma\tau\alpha} \quad (5.7)$$

The simulation is performed for a EuroTrough (ET-100) parabolic trough collector with an overall efficiency $\eta_{coll} = 0.765$ (Zarza et al, 2006). Hourly beam radiation on the moving surface of the collector (I_{bT}) is the hourly beam normal radiation (I_b) adjusted by the incident angle (θ)

$$I_{bT} = I_b \cos(\theta) \quad (5.8)$$

For a concentrator with continuous solar tracking, rotating in a north-south axis, the incident angle is related to the declination, δ as:

$$\cos(\theta) = \cos(\delta) \quad (5.9)$$

And, for a concentrator with continuous solar tracking, rotating in an east-west axis:

$$\cos(\theta) = \sqrt{1 - \cos^2(\delta) \sin^2(\omega)} \quad (5.10)$$

For the study, a solar field rotating in a north-south axis is used, because shading between collector arrays is diminished. Then:

$$I_{bT} = I_b \cos(\delta) \quad (5.11)$$

Finally, absorbed radiation in the receiver is:

$$\dot{Q}_{abs} = \eta_{coll} \cdot a \cdot L \cdot I_b \cdot \cos(\delta)$$

The working fluid used in the model is water and direct steam generation takes place in the receiver. Estimation of overall heat loss per unit area ($\dot{q}_L$) in function of working fluid temperature is difficult for direct steam generation because horizontal stratification occurs at the receiver with different phase distribution and consequently temperature distribution for each section. To simplify the analysis, correlations for $\dot{q}_L$ (Odeh et al. 1998) in W/m^2 in terms of local absorber outer surface temperature (T_{abs}) and ambient conditions are used:

$$\dot{q}_L = (a + c \cdot V) \cdot (T_{abs} - T_a) + \varepsilon_{ab} \cdot b \cdot (T_{abs}^4 - T_{sky}^4) \quad (5.12)$$

With:

- V : wind velocity,
- T_{abs} : absorber temperature ,
- T_a : dry bulb temperature,
- ε_{ab} : absorber emissivity,
- a, b, c : fitting constants, and
- T_{sky} : sky temperature.

The benefit of using a correlation as a function of absorber surface temperature (and not fluid temperature) is that it can be used for different working fluids and phase conditions. Parameters a , b and c are evaluated by curve fitting with heat loss data for specific collectors. For DSG tube with an absorber outer diameter D_o of 70 mm, an absorber inner diameter D_i of 54 mm, and a relation $D_i/D_o=54/70$, thermal equation coefficients are (Odeh et al. 1998):

$$\begin{aligned} a &= 1.91 \times 10^{-2} WK^{-1}m^{-2} \\ b &= 2.02 \times 10^{-9} WK^{-4}m^{-2} \\ c &= 6.608 \times 10^{-3} JK^{-1}m^{-3} \end{aligned} \quad (5.13)$$

A wind velocity annual average is used at each location, as shown in Table 5-2.

Table 5-2: Approximation of average wind velocity for each location
(from Sarmiento, 1995)

Location	Latitude	V (m/s)
1	19.08	8
2	22.32	11
3	27.83	9
4	30.23	6

A LUZ cermet coating covers the absorber and its emissivity is a function of the wall temperature (Forristal, 2003):

$$\varepsilon_{ab} = 0.000327 \cdot (T_{abs} + 273) - 0.065971 \quad (5.14)$$

To obtain overall heat loss, $\dot{q}_L$ is multiplied by absorber's area:

$$\dot{Q}_L = \pi \cdot D_o \cdot L \cdot \dot{q}_L \quad (5.15)$$

Fluid mean temperature (T_{bulk}) can be obtained using the relation:

$$T_{abs} = T_{bulk} + \frac{\dot{Q}_{fluid}}{\pi \cdot D_o \cdot L \cdot U} \quad (5.16)$$

The overall heat transfer coefficient (U) between the working fluid and the outer surface of the absorber tube is composed of a convective resistance R_{conv} between the HTF and the inner absorber surface and a conductive resistance R_{cond} among the inner and outer absorber surfaces as described in figure 5-3.

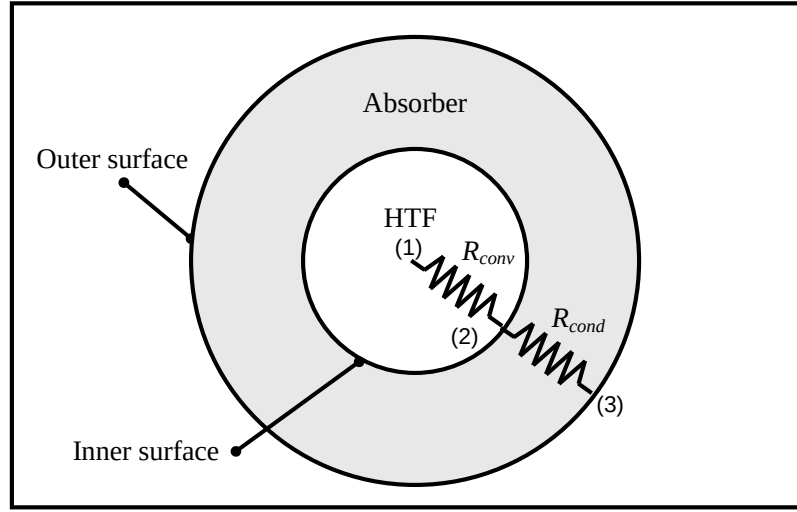


Figure 5-3: Resistance model of the heat losses between the HTF and the absorber.

$$U = \frac{1}{R_{conv} + R_{cond}} \quad (5.17)$$

The heat transfer convection resistance is a function of the heat transfer coefficient between the HTF and the inner absorber surface, $h_{conv,HTF \rightarrow abs,out}$:

$$R_{conv} = \frac{1}{h_{conv,HTF \rightarrow abs,in} \pi \cdot D_i} \quad (5.18)$$

The conductive resistance R_{cond} is a function of the absorber conductivity, k_{abs} and absorber dimensions:

$$R_{cond} = \frac{\ln(D_o / D_i)}{2\pi \cdot k_{abs}} \quad (5.19)$$

To evaluate U, the heat transfer coefficient of the working fluid ($h_{conv,HTF \rightarrow abs,out}$) shall be determined, which depends of the fluid phase.

An energy balance is performed in a control volume containing a collector segment of length L_{seg} , as shown in figure 5-4, using as input fluid properties at the point i like the fluid enthalpy h_i to obtain fluid properties in the next point $i+1$.

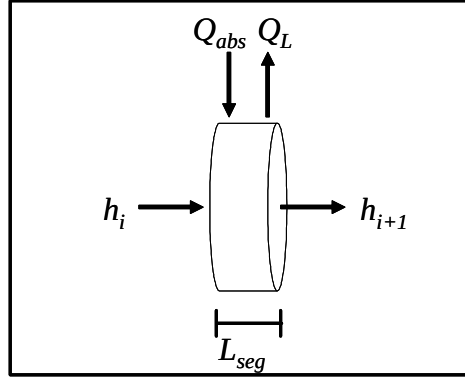


Figure 5-4: Energy balance in a collector segment.

Properties of the fluid at segment inlet (T_{in} , P_{in} , x , others) are known, but the properties at outlet are not. Also, to identify fluid useful energy gain ($\dot{Q}_{fluid}$), overall heat loss ($\dot{Q}_L$) must be known but it depends of the fluid bulk temperature T_{bulk} defined as the fluid temperature at the middle of the segment. This is solved estimating an initial value for outlet properties and fitting it by iteration to obtain the real value (Odeh et al. 1998).

Equations for each fluid phase are different so the analysis is separated in three regions: single phase water, two phase and dry steam.

a) Single phase water region:

For single phase water, $\dot{Q}_{fluid}$ is function of fluid bulk temperature difference within the section analyzed, between points i and $i+1$, mass $\dot{m}$ and heat capacity C_p of the HTF.

$$\dot{Q}_{fluid} = \dot{m} \cdot C_p (T_{bulk,i+1} - T_{bulk,i}) \quad (5.20)$$

Then, temperature at segment outlet is obtained from equation (5.17) and fluid enthalpy is simply found.

$$T_{bulk,i+1} = \frac{\dot{Q}_{fluid}}{\dot{m} \cdot C_p} + T_{bulk,i} \quad (5.21)$$

b) Two phase region:

In this region, temperature of the fluid is known, and the steam quality x defines the fluid energy. The energy balance for this region is:

$$\begin{aligned} \dot{Q}_{fluid} &= \dot{m} \cdot (h_{i+1} - h_i) \\ \dot{Q}_{fluid} &= \dot{m} \cdot ((x_i - x_{i+1})h_l + (x_{i+1} - x_i)h_g) \end{aligned} \quad (5.22)$$

Then, quality and enthalpy at segment outlet are obtained:

$$x_{i+1} = \frac{\dot{Q}_{fluid}}{\dot{m} \cdot (h_g - h_l)} + x_i \quad (5.23)$$

c) Dry steam region:

The energy balance for this region is:

$$\dot{Q}_{fluid} = \dot{m} \cdot (h_{i+1} - h_i) \quad (5.24)$$

Then, enthalpy at segment outlet is obtained from:

$$h_{i+1} = \frac{\dot{Q}_{fluid}}{\dot{m}} + h_i \quad (5.25)$$

Then, fluid's energy in the exit of the collector row is known and this values is the one required to estimate the plant backup requirements.

5.4 Backup requirement

Backup fraction is the fraction of the total energy required to reach temperature of the working fluid at 410 °C (as determined in equation 5.4) added by the fossil-fueled auxiliary boiler. Backup system operates in three different situations:

a) Daytime operation with lower solar radiation

The solar field has a critical radiation level I_c to operate, that means a minimum radiation at which energy absorbed in the receiver equals heat losses from the absorber element to the surrounding environment. Above this level the absorber element can start effectively collecting solar thermal energy. If solar radiation is less than I_c , then water should go from power cycle outlet to the backup heater inlet, without going through the solar field. In this scenario backup fraction equals 1.

$$\dot{Q}_{backup} = \dot{Q}_{tot} \quad (5.26)$$

$$f_{backup} = 1 \quad (5.27)$$

b) Daytime operation with backup

When fluid needs an additional heating after the solar field to reach 410 °C energy supplied and backup fraction are:

$$\dot{Q}_{backup} = \dot{m} \cdot (h_{in,turbine} - h_{out,sf}) \quad (5.28)$$

$$f_{backup} = \frac{\dot{Q}_{backup}}{\dot{Q}_{tot}} \quad (5.29)$$

c) Night operation (fossil fuel only mode)

If 24 hours operation is desired, during the night the plant becomes a regular fossil fuel plant, and total heat requirement is supplied by the fossil fuel heater. As a result backup fraction of the plant equals 1.

$$Q_{backup} = Q_{tot} \quad (5.30)$$

$$f_{backup} = 1 \quad (5.31)$$

Equations presented in this section are solved for the sunlight hours of each day of the month and during night hours a full backup is assumed.

5.5 EES Model

Solar field performance was modeled using the EES software that includes libraries of several fluids and material properties.

There are two alternatives to obtain the monthly backup requirement. The first one is to use the monthly means of solar radiation to obtain daily distribution for a mean day (assuming that all days of the month are equal to the mean day) and use this daily data as input in the model to obtain one day backup. Monthly backup requirement for this alternative is obtained multiplying daily backup by the number of days of the analyzed month. Considering utilizability issues (explained in section 4.3) of using a month with all days equal to mean day the second alternative is to use monthly means of solar radiation to create an artificial month to obtain daily distribution for each day of the month and use this radiation data for every hour of the month as an input in the model to obtain the monthly backup requirement.

The second alternative is more accurate than the first but the time required to run the model for a complete year in EES is 353 times greater. A comparison between these two

alternatives can be performed in order to compare differences between values and evaluate the necessity to construct the artificial month.

5.6 Summary

Total energy required to reach working fluid conditions at turbine inlet is known. How much of this energy is added in the solar field and how much by the backup system is function of radiation levels and collector performance. Then, if fluid properties at solar field outlet are estimated backup requirement can be obtained. A model of the solar field is performed in EES program using as an input the monthly mean data of solar radiation to obtain solar field outlet fluid properties and backup required for every second of the year.

6. NET ENERGY ANALYSIS

An important concern regarding energy harvesting systems is the status of the system as an energy source, carrier, or sink. Ideally, an energy system based on harvesting of renewable energy sources should produce more energy during its lifetime than the energy that is consumed during design, manufacturing, installation, operation and decommissioning. The NEA is a tool that allows us to find the system attributes and determine whether it is an energy source, carrier or sink. NEA consists mainly in identifying all the energy flows that were invested into, and generated by the system under analysis. The method output is the Net Energy (NE) parameter, defined as:

$$NE = E_{generated} - E_{invested} \quad (6.1)$$

If the NE is positive then the system is a net source of energy. If the NE is zero then the system is an energy carrier effectively converting one form of energy into another without significant gain or loss of energy. Finally, if the system NE is negative then the system is considered to be an energy sink and its implementation requires an energy subsidy that must come from other energy sources, thus compromising valuable energy that may be used for other productive processes. However, certain applications that display negative NE are vastly employed in specific market niches, such as batteries.

6.1 NEA history

The NEA is a fundamental tool that complements financial analysis for new energy technologies (IFIAS, 1975) considering that all energy resources are scarce and this scarcity increases over time, that energy scarcity imperils quality of life, and that society must focus on mitigating this scarcity by employing criteria of physical efficiency. The NEA dates from the 70's when the "technocrat" movement postulated that society should be led by engineers, with the financial systems based on fiat money replaced by an energy-value system in which the cost of goods and services would have to be based and denominated in energy units. In 1974 the US Congress passed public law 93-577,

the Federal Nonnuclear Energy Research and Development Act, in which it was stipulated that all prospective energy supply technologies considered for commercial application must be properly assessed and evaluated in terms of their potential for net energy production. Unfortunately, interest in NE has declined and adherence to this law was abandoned early on by the DOE because they believed that the benefits of NEA did not compensate the time and effort required (Herendeen, 2004).

An NEA can be composed by any of three different methodologies. Block (2007) has described these methodologies as (1) process analysis, (2) input-output analysis and (3) hybrid analysis.

6.2 Process analysis

Process analysis is the most common energy analysis. It accounts for all materials and energy flows within a system boundary in order to obtain a value for net energy. For all specific industrial processes, such as fossil fuels production or raw materials extraction or machine construction, net energy could be accounted for with the process analysis method if an accurate system boundary is established. Process energy requirement is accounted for the system considering two different forms of energy flows:

- Direct energy flows, such as fossil fuels, solar energy or electricity, and
- Indirect energy flows (also called energy carriers) such as materials, human labor or machinery use (Herendeen, 2004).

More accurate results are obtained when a more exhaustive life cycle inventory (LCI) of all materials required by the process are performed. Also, it must be considered that energy requirement for the process depends of the system boundaries and different results can be obtained if other sub processes are added to the system. Each analyst can define his own system boundary for the analysis. Then, different results for similar systems are often found in the literature.

6.3 Input-Output analysis

The input-output (I/O) analysis is an alternative method that accounts for energy flows in terms of monetary units, using energy intensity indicators ε_i or energy required per unit of monetary output generated for each sector of the country's economy. Then, energy intensity for sector i is defined as:

$$\varepsilon_i = \frac{\text{energy required by sector } i}{\text{monetary output of the sector } i} \quad (6.2)$$

Therefore, the input-output analysis requires the construction of an energy intensity matrix that must include all sectors of the economy that are relevant to the manufacturing and operation of the system under analysis. Each component of the I/O matrix, $X_{i,j}$, represents the goods and services (in monetary value) that sector i gives to sector j .

As a result, I/O analysis requires an enormous amount of data that includes almost every sector that helps define the gross domestic product (GDP) and their participation within GDP. Once the I/O matrix is constructed all monetary flows in the industry can be converted to energy flows by using energy intensity equivalences. The primary energy required to obtain a product of the sector i , is the book value \$bv times the energy intensity ε_i .

$$E_{\text{product sector } i} = \$bv \cdot \varepsilon_i \quad (6.3)$$

The hybrid method is a combination of process analysis and input-output analysis and it is used whenever energy and material flow requirements are not clear for a given process.

6.4 Net energy analysis as a evaluation tool

Net energy analyses have been performed for different sources of energy in recent years. Berglund et al. (2006) analyzed the energy performance of biogas production that in most cases resulted positive, estimating energy input and output during the lifecycle of the process. A complete scheme of the energy and material flows used in the process was developed, and the effect on final NE of using different materials or changing some sub-processes was analyzed. An interesting element in this work was the estimation of the energy cost for the electricity supply of the plant. This cost was identified to be dependent on the energy network in each region. Crawford et al. (2004) evaluated the NE for residential hot water systems obtaining energy payback times in order to compare different options. The procedure estimated the energy requirements due to the materials used in each part of the system and also the energy consumed during manufacture, assembly and transport of the system components. This study concluded that solar hot water systems provided a net energy saving compared to the conventional gas and electric systems. A system that has been also analyzed by NEA procedures is nuclear energy power generation. Store (2007) analyzed the energy requirements in nuclear energy power generation processes evaluating the direct energy requirements plus the embodied energy in the materials utilized. In most analysis it is considered that this embodied energy (also called Emergy) for raw materials equals zero. This assumption simplifies the analysis without losing accuracy in the results.

In some instances, the NEA has promoted discussions and debate around the adoption of new energy conversion and harvesting technologies. For example, Pimentel (2003) has criticized production of ethanol from corn crops, arguing that:

“29% more energy is used to produce a gallon of ethanol than the energy contained in a gallon of ethanol”, Pimentel (2003)

This openly contradicts the results of the United States Department of Agriculture who has concluded that the corn to ethanol process has a positive energy return over energy

invested (EROI) reaching at least a value of 1.34 due to the technological advances that increased the efficiency in crops farm production. As the NEA is one type of lifecycle analysis it must include all energy flows that are invested into and produced by the system, spanning from the design process until its decommissioning.

Similarly to an economic analysis, in which more expensive processes are identified and a minimum cost alternative is found, application of a NEA can help to identify energy-intensive processes within a systems lifecycle thus providing criteria for process replacement or improvement that can result in higher energy sustainability for a given system.

As described, NEA can be performed for many different processes and technologies. Performing an NEA for each new energy generation technology can bring additional information about the energy resource utilization.

Then, considering the potential of CSP plants as an electricity generation technology an NEA for a plant of 100 MW is performed in the present study for different locations in North Chile. This is in order to obtain sustainability indicators related to energy consumption and to define better locations from this point of view to develop the plants. In the next section, methodology used to obtain the NE for this plant, and details of the calculation of ER for direct and indirect energy flows are explained

6.5 Net energy analysis for PTC power plants in Chile

For four different locations in northern Chile, an energy balance of the plant is performed counting all energy flows generated in the different plant's lifecycle stages (Busted & Hancock, 1979). A net energy hybrid analysis is performed using predominantly the process analysis methodology and obtaining net energy for some particular sub processes from input/output tables only when other data is not available or the sub process is too complex to be analyzed by the regular method.

In what follows, a procedure is presented to obtain NE estimations for CSP plants located in different locations that have been defined as attractive for solar thermal power plants in Chile. Before complete the analysis a detailed system boundary must be defined.

6.6 System boundary

The first step in the analysis is the definition of an adequate system boundary. A global analysis is performed in this study and that implies that boundaries between countries are not considered. Anyway, in a global analysis a specific product (material, component or machine) have different energy content when it is located in different places around the world. Effectively, the energy cost of product transportation to final destination must be added to the “initial energy content” (content in the location where manufacture or extraction of the product is performed).

Energy contained in fuels (energy from the ground) and energy obtained directly from the sun in the form of solar radiation are not included as an input in a NEA analysis (R.Herendeen, 2004) mainly because NEA intends to define the energy cost or energy investment for the society to support a specific process. If energy resources are included the analysis would describe how they are converted into useful energy providing a physical efficiency of the process. Figure 6-1 displays a simplified energy flow diagram with all energy flows to and from the CSP plant included in the analysis.

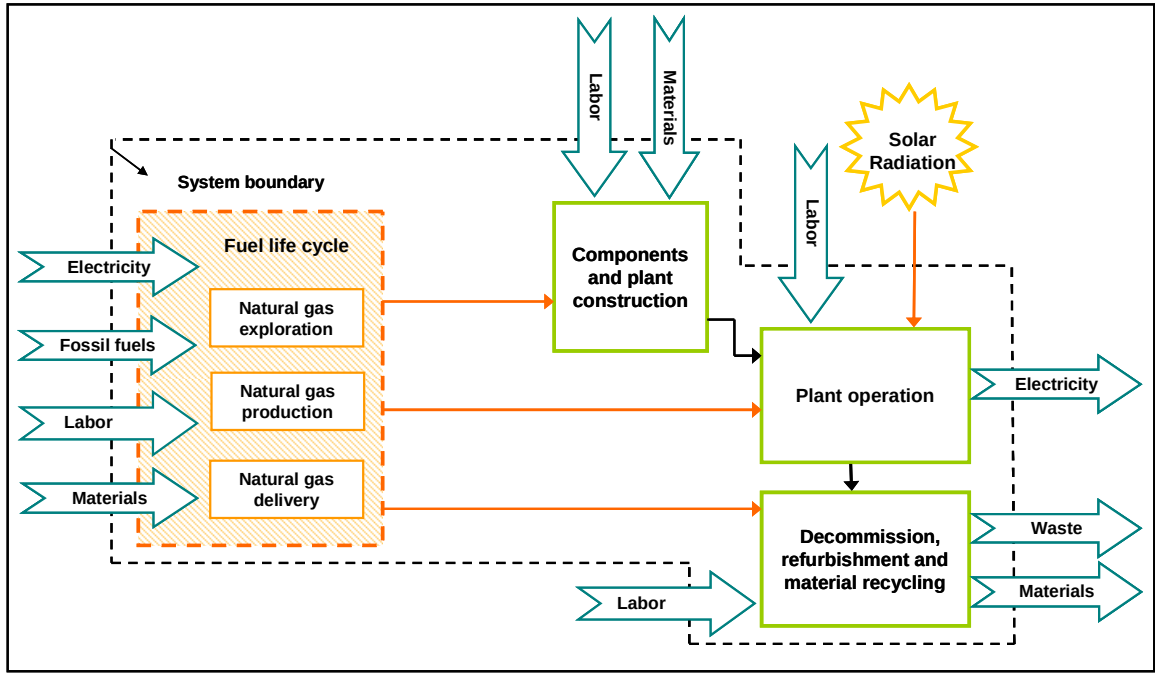


Figure 6-1: Energy inputs and outputs for the CSP power plant

As shown in the figure, energy input and outputs of the system (blue arrows) are materials, electricity, fuels, human labor, and waste. It is important to emphasize that fuel cycle is included in the system analyzed, and then, only the energy required to obtain a fuel (extraction, processing and delivery) is accounted for, not the energy contained in the fuel. The most important output from the lifecycle is the electricity generated by the plant as described in the next section.

6.7 Energy outputs generated by the plant

The plant output, energy generated in the form of electricity during its lifecycle in TJ is estimated as:

$$E_{electricity,LC} = P \cdot h_d \cdot days \cdot f_l \cdot y \cdot 0.0036 \quad (6.4)$$

With:

- P : Power of the plant, 100MW,
- h_d : hours of operation per day,
- $days$: days of operation per year,
- f_l : plant load factor,
- y : years of operation, and
- And 0.0036 is the unit conversion factor from MWh to TJ.

Load factor of the plant refers to the percentage of time in which the plant generates electricity. The plant does not generate continuously due to routine maintenance or eventual component failure, or in the case that the power plant is a peak power generation plant, which means its generation costs are so expensive that only generates on peak electricity consumption hours when electricity prices are high enough.

There are other energy flows that abandon the system boundary and take the form of waste and recovered materials. Energy recovered from materials is discounted to the energy requirement of materials accounted for as described in section 6.7.2.

6.8 Energy requirement of the plant

The next step is to obtain total energy inputs of the plant. Energy requirements of the CSP plant are separated by its lifecycle phases:

- Component manufacturing and plant construction, ER_{PC}
- Plant operation and maintenance, ER_{PO}
- Decommissioning, materials recycling and refurbishment of the location, ER_{DRR} .

$$ER_{LC} = ER_{PC} + ER_{PO} + ER_{DRR} \quad (6.5)$$

In order to accurately compute each component of this equation, all energy flows and production factors involved in the process must be accounted for and a suitable system boundary must be defined.

As explained before, NEA also takes into account indirect energy flows (also called production enablers) such as industrial machinery, their waste, human labor, and all the materials needed to manufacture final components, assuming that all inputs to the system are expressible in forms of energy. Energy content of production enablers is estimated by different methods and added as inputs/outputs to the energy analysis. Then, it is considered that energy flows into the system boundaries in the form of solar energy, electricity, fuels, human labor, and materials. Since solar energy is not considered as an energy input the energy requirement of each process or stage in the system is defined as:

$$ER_p = ER_{electricity} + ER_{fuels} + ER_{materials} + ER_{hl} \quad (6.6)$$

During the first part of the lifecycle when components are manufactured and the plant is being assembled only waste energy flows leave the systems boundary. Further, during the plant normal operation electricity is the most important energy output. Finally during plant decommissioning and materials recycling operations no electricity is generated, although recovered materials are discounted from material requirements of the plant. Internal or self energy consumption during the plant normal operation is subtracted from the plant electricity production. It is important to consider that it is difficult to account for all energy flows of the system because there is scarce data for process energy requirements. Therefore, only the most important and energy intensive process with known data points are analyzed and introduced into the model.

A particular method to obtaining ER for each component of equation 6.6 is performed in order to achieve a more precise value for the analysis. This methodology is described in the following sections.

6.8.1 Human labor energy requirement

It is indispensable to include energy flows added by human labor to the system analysis because human labor supports human life and is the most important component in the process, but not the most energy expensive. Even if human labor is replaced by a machine to perform a specific duty this machine is build and maintained with human labor and is going to need additional energy to work. This indicates that productive factors in a process (capital, human labor and energy) are substitutes yet it must be considered that in some processes large increase of money is needed to replace a little decrease of energy and in other processes human labor is irreplaceable.

Two ways are used by different authors to evaluate energy embodied in human labor. The first approximation is to consider the amount of energy that is physiologically needed by a worker to perform an intended task. A reasonable estimation can result from assuming that this energy requirement is equivalent to the energy input by feeding. Then, the energy added by human labor is the mean energy consumed by workers in one day estimated from nutritional information to be 2000 *kcal/day*, equivalent to energy consumed in the form of food by the worker. Then, the energy contribution for hour of human labor is approximately:

$$EM_{hl} = \frac{2000 \cdot kcal}{day} \cdot \frac{4.187 \cdot kJ}{kcal} \cdot \frac{day}{8 \cdot h_w} = 1046.75 \frac{kJ}{h_w} \quad (6.7)$$

The second alternative is to count energy as a function of the effective work performed that is more accurate because it incorporates dissimilarity between different kinds of jobs. There are many studies that calculate calorie consumption for different activities with a physical activity monitoring system or using indirect calorimetry (Kruskall et al, 2004). For a worker of 80 kilograms weight, energy consumption for a heavy intensity duty (i.e. building roads, construction work, coal mining) is approximately 495 *kcal/h*, for medium intensity duty (i.e. maintenance, cleaning or painting) is 390 *kcal/h* approximately and for light intensity duties (i.e. office work, attending a meeting or writing in the computer) 190 *kcal/h* approximately (The fitness partner connection,

2008). It should be considered that it is very probable that a worker does not perform same intensity duties all the time. Considering different intensities during day, workers are classified in 3 groups. Approximations of energy spend for each group is displayed in Table 6-1.

Table 6-1: Energy expenditure for different groups of workers

Group	Type of duty	h_{HI}	h_{MI}	h_{LI}	$kcal/day$	$kcal/h_w$	kJ/h_w	Wh/h_w
1	Engineers, administration	0	0	8	1520	190	796	221
2	Maintenance worker	1	5	2	2825	353	1478	411
3	Construction worker	5	2	1	3445	431	1804	501

h_{HI} : Hours of high intensity work.

h_{MI} : Hours of medium intensity work.

h_{LI} : Hours of light intensity work.

h_w : Hours of work (8 hours).

It is important to consider that this estimation does not reflect most important contribution of human labor to the system: intelligence, which provides them the faculty to learn new duties and to solve problems, something that machines are not able to achieve. Also, technology development and fuel use improves the productivity of human labor.

If human resources of each kind of work needed annually ($n_{hl,k}$) are known, human labor energy requirement is obtained as:

$$ER_{hl,year} = \sum_{k=1}^3 n_{hl,k} \cdot EM_{hl,k} \cdot h_{w,year} \quad (6.8)$$

6.8.2 Energy content of materials

Energy content for different materials has already been estimated by several authors, denoted as embodied energy or emergy (EM) and defined as the energy added to materials through the application of heat, electricity, fuels or by performing work to the system in order to acquire its final properties (Herendeen, 2004). To simplify the analysis it is assumed that raw materials have no embodied energy. Regarding building materials and metals, Chapman and F. Roberts (1983), and Ventakatarama et al. (2003) have proposed that their emergy can be estimated as the sum of the energy flows required for extraction and processing of the material:

$$EM_{materials} = ER_{EX} + ER_{PRO} \quad (6.9)$$

It is important to consider that NEA's purpose is to define the energy cost for the society to support a specific process, and subsequently chemical energy content of the material (maximum energy that can be obtained from the material's combustion reaction or gross calorific value) is not included in mainly studies.

Most data for energy used in the analysis was obtained in a recompilation from different studies prepared by Busted and Hancock (1979). Values for materials emergy used in this analysis are in Table 6-2.

To obtain materials energy requirement a LCI for the plant lifecycle is performed. Recovered materials from recycling in plant decommissioning are discounted from material requirements of plants construction and operation phases.

$$ER_{materials} = ER_{materials,PC\&PO} - E_{materials,DRR} \quad (6.10)$$

Table 6-2: Energy content for different materials

Material	Energy GJ/ton	Energy MWh/ton
Aluminum	222	61.6
Chromium	82.9	23
Concrete	1.2	0.33
Copper	83.26	23.1
Iron	21.27	5.91
Carbon Steel	25.94	7.21
High alloyed steels	53.1	14.75
Manganese	51.5	14.3
Molybdenum	378	105
glass	25.09	6.96
silver	128.18	35.6

Also, energy costs of transport to final destination, $E_{transport}$ (explained in section 6.7.4) must be added to material energy. Then, energy requirement for m kilograms of material i using material energy (EM_i) is:

$$ER = m_i \cdot EM_i + E_{i,TR} \quad (6.11)$$

Requirements for especially constructed structures are easy to account for but materials embodied in machineries or complex components of the plant such as pumps or heaters it is difficult to be estimated.

First alternative to obtain energy content of complex components is to use the GEMIS database (GEMIS, 2008). This database has been developed by the Öko-Institut and Gesamthochschule Kassel (GhK) and contains energy costs estimations for many processes and components. The database is free and upgraded continuously.

A second alternative is to use data referred to these components from input-output analyses, using the cost of the equipment and energy intensities in TJ/\$ for the sector. There is no data from the Chilean economy to construct a Chilean I/O matrix. Fortunately, for all sectors of the United States economy energy intensities are available (Green Design initiative, 2001) and can be used with the assumption that equipments can be imported from the USA, adding the respective energy cost of transportation. Then, using the I/O method the energy requirement for a component j of the system with cost $\$C_j$ and energy intensity ε_j is:

$$ER_j = C_j \cdot \varepsilon_j \quad (6.12)$$

6.8.3 Fuel cycle

For fossil fuels the emergy can be obtained by considering the energy flows of each process in fuel's lifecycle. A typical fossil fuel lifecycle includes exploration, production and delivery of the resources:

$$EM_{fuels} = ER_{EX} + ER_{PR} + ER_{DE} \quad (6.13)$$

Energy input from fossil fuel is an important component in power plant's NEA, because the process to achieve the final product is energy intensive. Therefore, considering a high fossil fuel backup fraction it can become the most expensive process in the power plant LC. In this situation, net energy of the plant and its status as an energy source becomes dependent of fossil fuel utilization.

Natural gas is the most significant source of energy in north Chile, as seen in figure 1-2, reaching a 58,6% of electricity generation. Assuming that a hybrid PTC power plant is going to be installed in north Chile, the most probable backup fossil fuel to be used for the plant must be natural gas (NG), considering the current distribution system and fuel availability. Any fossil fuel could be used for the hybrid power plant, but taking into

consideration fossil fuel availability and the lower environmental effects of using NG instead of coal or diesel, this alternative is analyzed in the present study.

In 2007, 55,3% of natural gas consumption in Chile was supplied by Argentina. However, in northern Chile it becomes 100%. The north Chile distribution system has 2 international connections: Gasatacama pipeline and Norandino pipeline that mainly satisfy power plants and mining operations. The Taltal pipeline expand the Norandino pipeline from Mejillones to Taltal to provide NG to power plants in the region.

GasAndes pipeline, on the other hand, connects central Chile with the Neuquén gas basin and delivers from central valley to Quillota (the central valley gas system northernmost gate) via the Electrogas pipeline. The pipeline system maps are displayed in the figures 6-2 and 6-3.

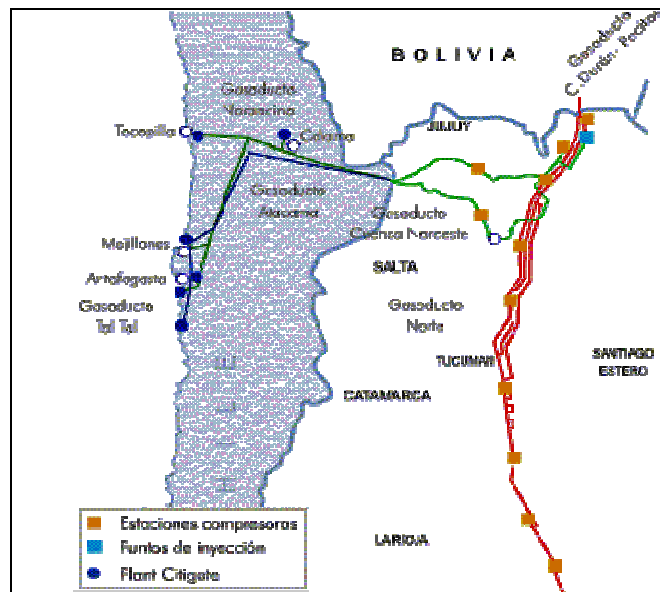


Figure 6-2: North Chile NG Pipeline system. (CNE, 2008)

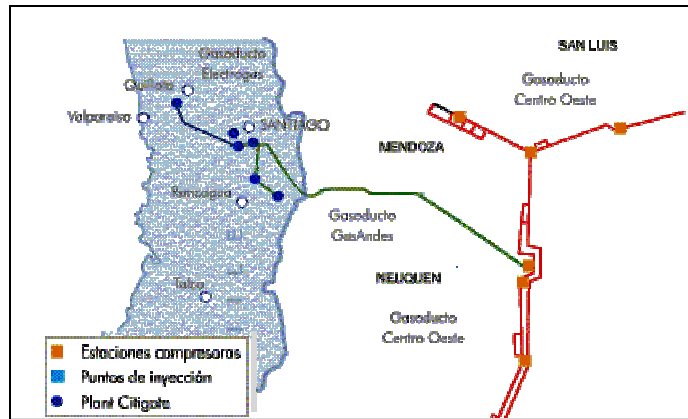


Figure 6-3: Central Chile NG Pipeline system. (CNE, 2008)

To obtain fuel backup for the plant a new pipeline connection must be completed and its energy costs must be included as part of the fuel cycle.

Total production of Argentina's principal sources for Chile (North-west and Neuquén basins) peaked in 2004, as shown in the figure 6-4 (Secretaría de Energía de la Nación Argentina, 2008). If there are not new discoveries and investment in the area, it is expected a depletion of the resource in the near term and new sources of NG must be used.

As an alternative to natural gas from Argentina, liquefied natural gas could be used as a backup for the plant. An international LNG terminal for ship imports is under construction in Quintero (near Valparaíso) and a project to construct a second terminal in Mejillones is being analyzed. As Quintero terminal does not operate at present and data about the GNL source is no available, this alternative has not been analyzed in this study.

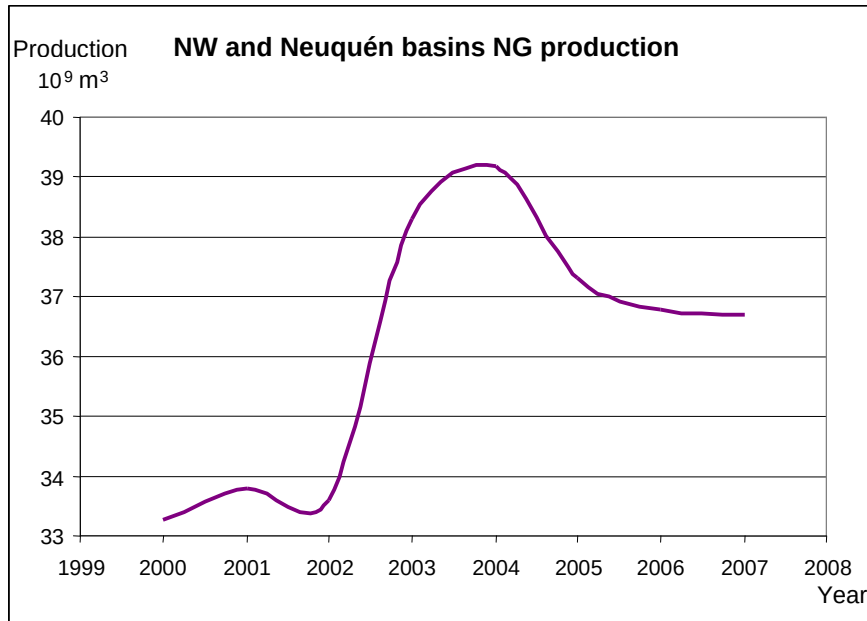


Figure 6-4: Total production from 2000 to 2007 for NW and Neuquén basins in thousand millions of m³

a) Delivery:

Energy costs of fuel delivery take account of additional transport pipeline construction (materials and installation energy costs), transmission fuel losses and energy cost of adding compressor stations (if needed).

$$ER_{DE} = E_{transmission\ loss} + E_{pipe\ materials} + E_{pipe\ installation} + E_{compressor\ station} \quad (6.14)$$

Average delivery energy losses are estimated based on data of natural gas balance from CNE (Comisión Nacional de Energía), as seen in Table 6-3, obtaining a production/delivery ratio ($r_{p/d}$) for Chile. Then, transmission energy costs are a function of total fuel delivery to plant (or total energy content $E_{f,d}$ delivered to the plant):

$$E_{transmission\ loss} = E_{f,d} \cdot (r_{p/d} - 1) \quad (6.15)$$

Table 6-3: Production/delivery ratio for NG in Chile

Natural gas exploration	
Energy cost of exploration (GJ/GJ)	0.00644
NG imports, 2007 (10^6 m^3)	2495
NG production, 2007 (10^6 m^3)	2012
NG total input, 2007 (10^6 m^3)	4507
NG total deliveries, 2007 (10^6 m^3)	4426
NG production/delivery ratio ($r_{p/d}$)	1.0183

To obtain energy costs of pipeline construction, the distance from CSP plant locations to nearest gas pipeline is estimated, using pipeline system maps (figures 6-2 and 6-3).

Properties of pipeline section where new transport pipelines can be connected for each proposed location are shown in Table 6-4. Diameter selected for new pipelines is the same of the section where they are connected. To increase pipeline capacity to deliver new plant NG requirement, a new compressor station must be installed to increase average pipeline pressure (Thomas and Dawe, 2003).

Table 6-4: CSP plants locations nearest NG Pipelines properties.

Location	Nearest Pipeline	Pipeline Section	Pipe Diameter (inches)	Capacity MMm3/ day
1	Gasatacama	Paso de Jama/ Mejillones	20	8.5
2	Gasatacama	Paso de Jama/ Mejillones	20	8.5
3	Taltal	Mejillones-La Negra	16	2.4
4	Electrogas	Maipu-Quillota	24	4.1

Energy embodied in 1 mile of pipe materials is estimated with material content of the section m_{has} (high alloy steel in tons) and energy for the material (from table 6-2) as:

$$EM_{pipe\ materials} = m_{has} \cdot EM_{has} \quad [GJ / mile] \quad (6.16)$$

And materials energy cost for a pipeline with L_{pipe} length is:

$$E_{pipe\ materials} = L_{pipe} \cdot EM_{pipe\ materials} \quad (6.17)$$

Energy required for pipeline installation is obtained with I/O energy as a function of pipe diameter (Meier, 2002) per mile.

$$E_{pipe\ installati\ on} = L_{pipe} \cdot EM_{pipe\ installati\ on} \quad (6.18)$$

b) Production:

Energy required for NG production ($ER_{f,PR}$) includes natural gas required for well and field operations, vent and flare losses (gas released into the air, or burned during production) and fuel processing requirements:

$$ER_{f,PR} = ER_{FOP} + ER_{VF} + ER_{FP} \quad (6.19)$$

Vent and flare losses and processing plant requirement can be obtained from statistics data for a similar industry, but energy required for well and field operations depends of the resource quality and well accessibility, being distinctive for each location. Data for Argentina are not available, and an alternative method must be used. Energy requirement for production can be also obtained as function of EROI index (energy return E_{return} over energy invested $E_{invested}$), defined as:

$$EROI = \frac{E_{return}}{E_{invested}} \quad (6.20)$$

Maximum energy that can be obtained from the fuel (or energy return) E_f is determined by its chemical energy (high heating value: HHV). Each gas source has a particular HHV and a mixture from different sources is needed to obtain a constant E_f . Then, efficiency and EROI of fossil fuel production are defined as:

$$\eta_{f,PR} = \frac{E_f}{E_f + ER_{f,PR}} \quad (6.21)$$

$$EROI_{f,PR} = \frac{E_f}{ER_{f,PR}} \quad (6.22)$$

A relation between production efficiency and EROI is obtained, defined as:

$$\frac{1}{\eta_{f,PR}} = \frac{1}{EROI_{f,PR}} + 1 \quad (6.23)$$

Behavior of process efficiency v/s EROI is displayed in figure 6-5.

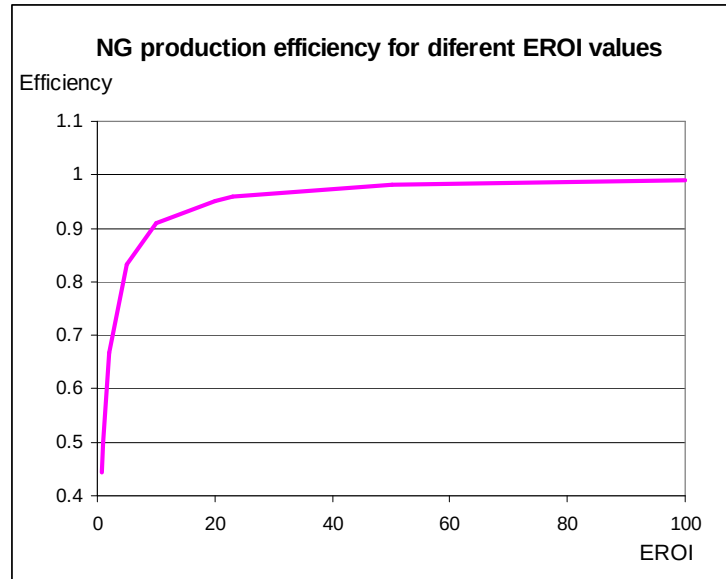


Figure 6-5: Process efficiency v/s EROI, for NG production.

If lifetime production of natural gas required for the plant ($E_{f,p}$) is known, energy required for fuel production (or energy invested) is obtained as:

$$ER_{f,PR} = \frac{E_{f,p}}{EROI_{f,PR}} \quad (6.24)$$

Energy input to the plant from fuel lifecycle for high backup fractions have a significant participation in NEA, so the value of EROI for fuel production is one of the most important variables in the analysis. But the specific value of EROI for Argentinean NG production is not known, and there is no sufficient data available to obtain an accurate estimate.

An EROI of 23 was estimated for NG in the US in 1984 (Cleveland and Constanza, 1984). This value was 100 in 1930 and 20 in 2000 (Cleveland, 2005) confirming a decrease of the EROI over time. The cause of this decrease can be attributed to quality changes in natural gas resources due to the fact that ores with higher quality (and better accessibility) are exploited first. The exploitation of more complicated wells with lower law resources requires the use of expensive technologies in energy terms. This means that the increase of production energy costs generate a decrease of the EROI. Some authors attribute this EROI decrease to resource depletion. Technological development also influences the EROI value reducing energy costs, but the rate at which technological development decreases energy costs is lower than the rate at which quality changes in natural resources increases energy costs.

In a more recent study in 2005 an EROI of 10 was obtained (Hall, C. et al, 2008) from time series for Pennsylvania, but the author explains:

“There is no readily available literature either on, or by which, one might derive the Energy Return on Investment (EROI) of Natural Gas. Published summaries of natural gas reservoir studies and general overviews of drilling practices are

sparse. Even with such a broad study, it would be difficult to assess natural gas production generally because each kind of operation is very field- specific"(Hall, C. et al, 2008).

A summary of EROI estimations for natural gas in USA is displayed in Table 6-5.

Table 6-5: Estimations of EROI for natural gas in USA

Natural Gas in US	Year of the estimation	EROI
Cleveland, 2005	1930	100
Cleveland and Constanza, 1984	1984	23
Cleveland, 2005	2000	20
Hall, C. et al, 2008	2005	10

Then, it can be concluded that EROI for a specific field is difficult to obtain. However, EROI can be estimated comparing values for similar fields. Argentinean fields in the NW and Neuquén basins are in a similar stage of development than fields in USA (at some point after their production peak). It is assumed that EROI for these locations are at some point between 30 and 10. For the analysis a constant EROI of 15 is used.

c) Exploration:

It is assumed in this study that exploration industries have similar operation systems. Then, exploration industry in USA can be used as reference in the analysis. Many studies in this area have been performed in the USA and energy costs for fuel exploration data from their I/O matrix is available. Average energy intensity of exploration ε_{EX} for USA is 0,00644 GJ/GJ (Meier, 2002). To obtain the total energy cost of exploration, (1) the required lifetime production of natural gas must be known and (2) the production/delivery ratio ($r_{p/d}$) is needed to include

system delivery losses. Then, NG required lifetime production ($E_{f,p}$) is $r_{p/d}$ times fuel delivery to plant ($E_{f,d}$):

$$E_{f,p} = r_{p/d} \cdot E_{f,d} \quad (6.25)$$

And exploration energy requirement is:

$$ER_{EX} = \varepsilon_{EX} \cdot E_{f,p} \quad (6.26)$$

6.8.4 Electrical energy requirement

To determine electricity energy input, the total energy obtained from electricity consumption must be transformed to primary energy. That means to go backward in the electricity production process which has four stages (Boustead and Hancock, 1979), each one with a respective efficiency:

- Primary fuel production: η_1 .
- Primary fuel delivery: η_2 .
- Conversion to electricity: η_3 .
- Delivery of electricity (transmission): η_4 .

Then, overall efficiency η of electricity production is given by:

$$\eta = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_4 \quad (6.27)$$

Electricity is converted to primary energy applying these efficiencies, or his equivalent called primary conversion factor, defined as:

$$pcf = \frac{1}{\eta} \quad (6.28)$$

Efficiencies for different power plants are known and primary fuel production and delivery efficiencies can be easily obtained (Boustead and Hancock, 1979). Then, the first three efficiencies, which defines the electricity production process ($\eta_{pp} = \eta_1 \cdot \eta_2 \cdot \eta_3$) are known. To obtain the mean primary conversion factor for northern Chile power plants, the participation of each type of power plant in the SING is used (CNE, 2007), as shown in Table 6-6.

Table 6-6: Primary energy conversion factors for SING matrix

Power plant	Power installed [MW]	Power installed [%]	Primary energy conversion factor
Coal	1205.6	33.5%	2.81
Diesel	144.1	4.0%	2.70
Fuel Oil Nr. 6	127.6	3.5%	2.70
Natural Gas	2111.7	58.6%	1.96
Hydro	12.8	0.4%	1.00
Total Power Installed	3601.9	100.0%	2.30

Then, mean primary energy conversion factor for Chilean power plants is 2.3 with a respective efficiency $\eta_{pp} = 0.44$. Considering transmission losses of 10%, mean total primary energy conversion efficiency for Chilean electricity becomes:

$$\eta = \eta_{pp} \cdot \eta_4 = 0.44 \cdot 0.9 = 0.39 \quad (6.29)$$

And mean primary energy conversion factor is:

$$pcf = 1/\eta = 2.552 \quad (6.30)$$

Finally, for an electric consumption EC , energy requirement is obtained as:

$$ER_{electricity} = EC \cdot pcf \quad (6.31)$$

6.8.5 Transportation energy requirement

Material and component transportation to final destination is an energy intensive process mainly because in most cases involves the use of fossil fuels. Also, transportation is one of the sectors with the largest growth in energy use (Block, 2007) due to the increases in vehicle sizes. Energy use for different modes of freight transportation varies for different technologies; however an average values is used in this study. For a freight of mass m_i , transported d km, by a technology with energy use of T_i MJ/tones-km, the energy cost of transportation is:

$$E_{i,TR} = m_i \cdot d \cdot T_i \quad (6.32)$$

Energy use for a generic ship with capacity 16000 ton is 1,311 MJ/tones-km and for a generic truck with freight capacity of 20 tones is 0,981 MJ/tones-km. The biggest port in northern Chile for machinery freight importation is Antofagasta, with the port of Iquique as an alternative. The nearest port for each location is considered. Therefore for location 1 Iquique is used and for location 2, 3 and 4 Antofagasta becomes more convenient.

6.9 Sustainability indicators: EROI and Energy payback time.

Two indicators were evaluated for this study:

- **Energy return over investment**, defined as the sum of energy flows produced by an energy conversion system divided by the sum of energy flows invested in the system's lifecycle (equation 6.20), and
- **Energy payback time (EPT)**, defined as the time (in years) that it takes the CSP plant to generate an amount of energy equivalent to the cumulative energy that was invested at the time analyzed :

$$EPT = \frac{CE_{invested}}{E_{generated, year}} \quad (6.33)$$

$$CE_{invested} = NE_{PC} + CE_{fuels} \quad (6.34)$$

Where $CE_{invested}$ is the cumulative energy invested, and CE_{fuels} is the cumulative energy contained in the fuels, considering the total time from the plant's first operational day until its decommissioning.

Both indicators are suitable to compare different alternatives, in a similar form as economic indicators are used by economists.

6.10 Summary

NEA can be performed for many different processes and technologies in order to obtain an effective life cycle net energy production while defining the system's sustainability from the energy resource conservation perspective.

Considering the potential of CSP plants as an electricity generation technology, a NEA for a PTC plant of 100 MW was performed at different locations in northern Chile, in order to (1) obtain NE, (2) calculate sustainability indicators related with energy consumption and (3) define better locations in energy terms to develop such plants. The hybrid method of NEA was used as a combination of process analysis and input-output analysis.

To obtain NE of the plant lifecycle, an inventory of all ER of direct and indirect energy flows must be completed. Energy flows through the system boundaries in form of electricity, fuels, human labor, and materials. Fuels energy content (energy from the ground) and energy obtained directly from the sun in the form of solar radiation are not included as an input in a NEA mainly because NEA tries to define the energy cost or

energy investment for the society to support a specific process. Then, NEA determines energy resources utilization for a specific process.

Power plant lifecycle is separated in three phases to simplify the analysis: (1) component manufacturing and plant construction, (2) plant operation and maintenance and (3) decommissioning, materials recycling and refurbishment of the location. Fossil fuel lifecycle is included in the defined system boundary and backup requirement of the plant during the entire lifecycle is one of the most important components of the analysis.

7. RESULTS AND DISCUSSION

A parabolic trough collector power plant is selected from the available CSP technologies to perform the present study mainly due to its development status and reduced electricity generation costs as explained in section 2. A large amount of data for this technology has been gathered in order to understand differences between different PTC plant configurations and to obtain enough data to perform the lifecycle NEA of the plant. A hybrid direct steam generation PTC power plant has been selected as the best alternative to be analyzed considering the benefits of DSG and the necessity to integrate an additional system to provide continuous electricity supply.

NEA was performed on the hybrid PTC power plant in order to define life cycle system energy resource consumption and sustainability indicators. An important component in plant lifecycle was the backup required by the plant to maintain a constant output of 100 MW. Required backup is a function of the solar radiation level at each location where the plant is installed. In this study, NEA was used as a tool to select the best locations from a sustainability point of view.

To obtain the life cycle backup energy requirement of the plant for each location a model in EES is performed using monthly mean radiation data as input.

7.1 Direct solar radiation for each location

Performing EES, direct component of solar radiation was obtained for each location from the monthly means. Hourly global radiation (I) and hourly beam radiation (I_b) for each hour of a day were estimated using daily radiation distribution. Thus both components for the mean day of each month or for each day of an artificial month were calculated, depending on the alternative selected.

As an illustration, considering the large amount of data obtained for both components for each hour of the year for each location (more than 37 thousand values), only results for location 1 in January are displayed in this thesis. As shown in Figures 7-1 and 7-2, where three days of an artificial month are displayed day radiation has a peak in midday and a regular distribution. However, for real data variability is expected due to the presence of clouds. Also it is important to keep in mind that beam radiation (component that is used by the collectors) is a component (and lower) of total radiation.

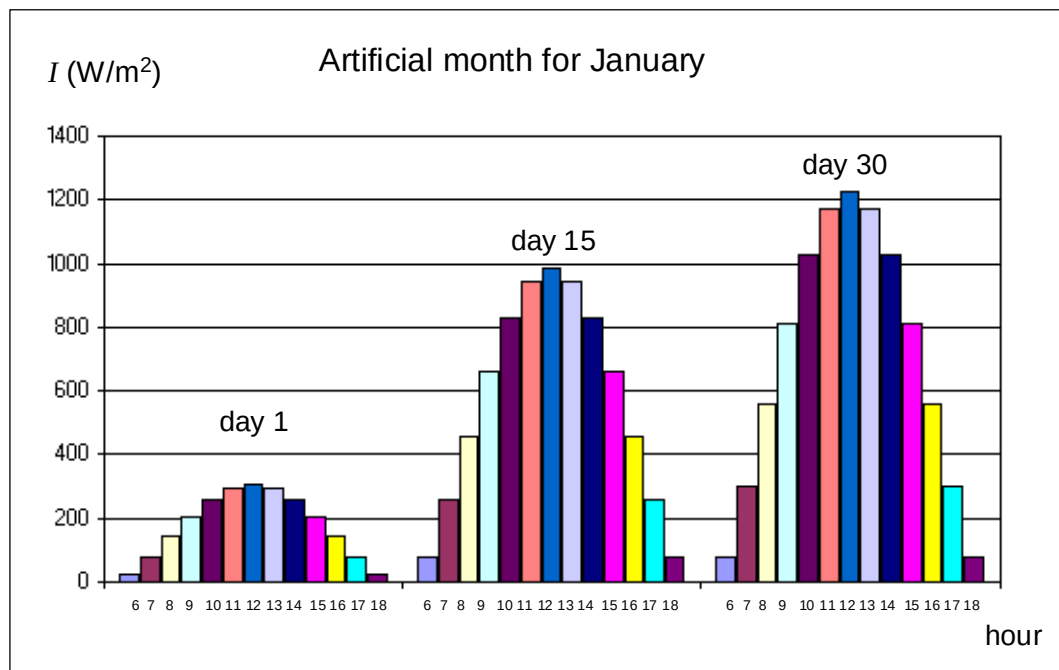


Figure 7-1: Hourly global radiation for different days of January at Location 1.

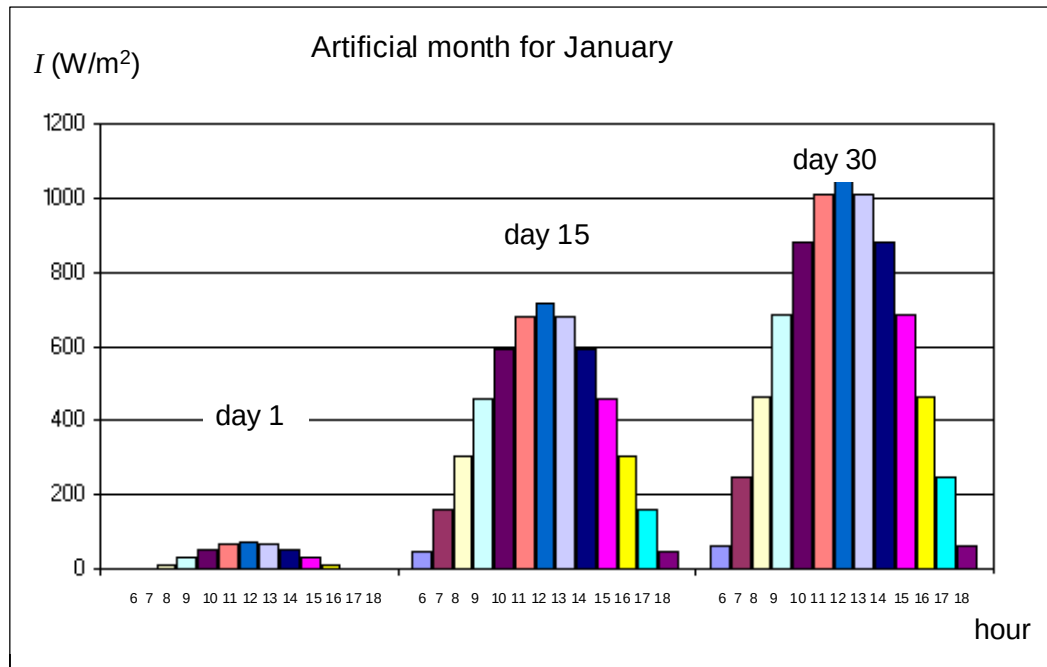


Figure 7-2: Hourly beam radiation for different days of January at Location 1.

This data was required to model plant performance in EES, at each hour of the year to size yearly backup requirement of the power plant.

7.2 First approximation to obtain a estimation of a backup fraction

Results obtained for the first estimation of the backup requirement using equations 5.1 to 5.3 results in a backup system that operates between 60% and 90% of the year for selected locations. As seen in figure 7-3 locations 1 and 2 seem to require less backup during the year than locations 3 and 4 to maintain a 100 MW output level. Also, the highest backup fractions were obtained for winter months reaching values slightly lower than 90% in the least favorable location. Minimum backup fractions occur in summer reaching a 60% for the most favorable month at location 1.

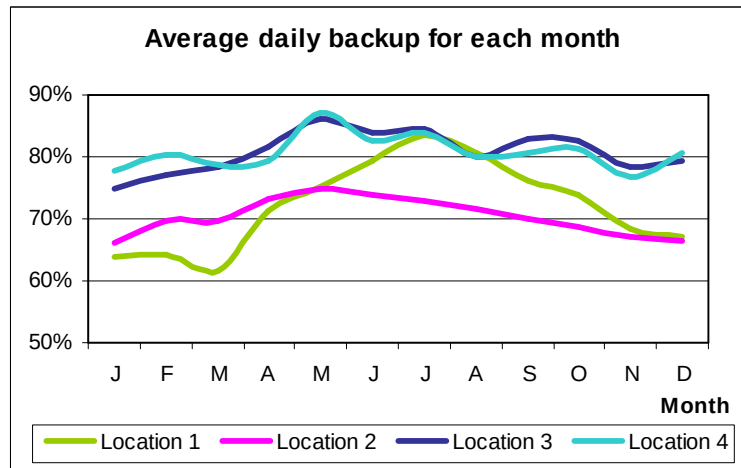


Figure 7-3: First approximation of average daily backup for each month.

These values may be used as a reference. It is expected that in a more accurate analysis locations 1 and 2 also display better values than locations 3 and 4. Considering the simplified approach and its overestimation, results obtained are considered an upper limit to future analyses results.

7.3 Comparison of backup results from EES model

Total energy needed to heat the working fluid to 410°C by hour is 1358GJ/hour. Some of this energy is added in the solar collector field and the rest by the backup system. To obtain the fraction of energy added in the solar field, a model of the system is performed in EES. With the solar fraction, the total energy added by the backup system is calculated.

As shown in section 5.5, two alternatives of monthly backup requirement from the EES model can be used. The first is to model the mean day of the month and estimate monthly backup requirement multiplying daily backup by the number of days in the analyzed month. The second is to model each day of an artificial month created from monthly mean radiation data. Second alternative is more accurate but requires more

computing time. For the study, both alternatives have been performed for each month of the year for one location (location number 1) in order to obtain the difference between results and determine if it is necessary to perform the more accurate alternative for all locations. Results from EES of the backup requirement for each alternative are displayed in Table 7-1.

Table 7-1: Monthly backup for each location obtained from EES model, using a month with identical days and an artificial month.

Backup (TJ)	J	F	M	A	M	J	J	A	S	O	N	D	Total
Month with identical days	289	271	280	371	415	424	462	431	374	368	310	319	4.314
Artificial month	229	211	225	282	324	338	387	362	311	299	251	252	3.471
Difference %	26,2	28,4	24,4	31,5	28,1	25,4	19,4	19,0	20,3	23,1	23,5	26,6	24,3

As shown in this table values obtained by modeling a month with identical days are higher than values obtained by modeling the artificial month with a range of 20% to 32%. There is a clear relationship between the results as seen in figure 7-4 that display high values of backup requirements in winter for the two model results. It is important to emphasize that both results obtained from EES have also a similar distributions during the year than results obtained in the first estimation, as displayed in figure 7-3.

A difference between the two results that is higher than 5% is considered inaccurate and cannot be used as input in the NEA mainly because backup requirement has the most effect on the analysis.

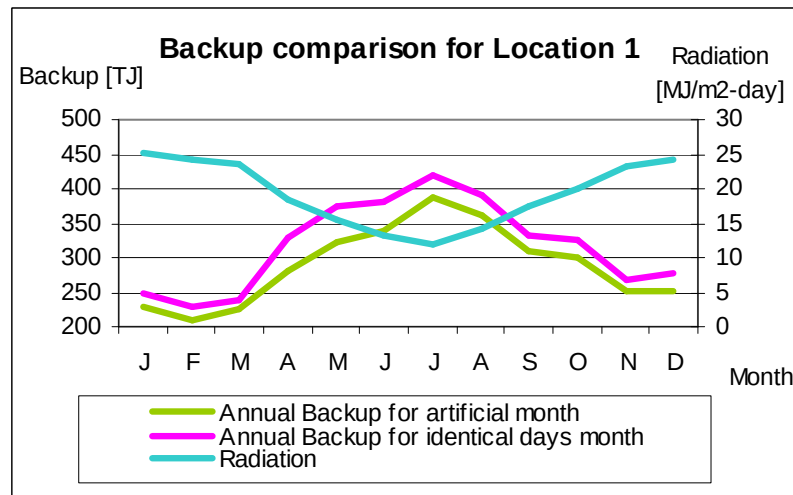


Figure 7-4: Backup for each location obtained from EES model, using a month with identical days and an artificial month, and monthly mean radiation.

The alternative of modeling a month with identical days provides underestimations of utilizable energy and consequently overestimates backup requirements by more than 20%. Thus an artificial month must be fabricated from monthly means radiation data for each location to obtain more accurate results in the simulation.

7.4 Backup requirement obtained using an artificial month

More accurate results for backup requirements are obtained simulating solar field performance in EES by using an artificial month fabricated from monthly mean radiation data as explained in Chapter 5. The EES model estimates backup requirement for sunlight hours for each hour of the artificial month and adds these values to obtain monthly backup. Results for the four analyzed locations, and total energy required by the system to reach working fluids properties are displayed in Table 7-2.

Table 7-2: Monthly backup for each location, obtained using an artificial month and total monthly energy required.

Backup (TJ)	J	F	M	A	M	J	J	A	S	O	N	D	Total
Loc. 1	229	211	225	282	324	338	387	362	311	299	251	252	3.471
Loc. 2	255	242	273	293	321	301	298	291	262	259	238	255	3.286
Loc.3	309	282	325	344	387	366	382	355	359	366	330	344	4.150
Loc.4	311	288	311	312	384	343	363	333	323	334	295	335	3.932
Total Energy Requirement	547	494	547	530	547	530	547	547	530	547	530	547	6.444

The backup fraction for each month is between 40% and 70%, as shown in Table 7-3. As shown in Figure 7-5, location 2 has the lowest backup requirement during most months of the year and is also the location with the lowest yearly backup requirement, as shown in table 7-2. Location 2 has the lowest variations during the year that can be an advantage was the plant is implemented at this location.

Table 7-3: Monthly backup, as percentage of total energy required.

Backup (%)	J	F	M	A	M	J	J	A	S	O	N	D
Loc. 1	41,9	42,7	41,1	53,2	59,2	63,8	70,8	66,1	58,7	54,6	47,3	46,0
Loc. 2	46,5	49,0	49,9	55,2	58,6	56,8	54,4	53,1	49,6	47,3	45,0	46,5
Loc.3	56,5	57,1	59,4	65,0	70,8	69,0	69,9	64,9	67,8	66,8	62,2	62,9
Loc.4	56,8	58,3	56,7	58,9	70,2	64,8	66,3	60,8	60,9	61,0	55,7	61,3

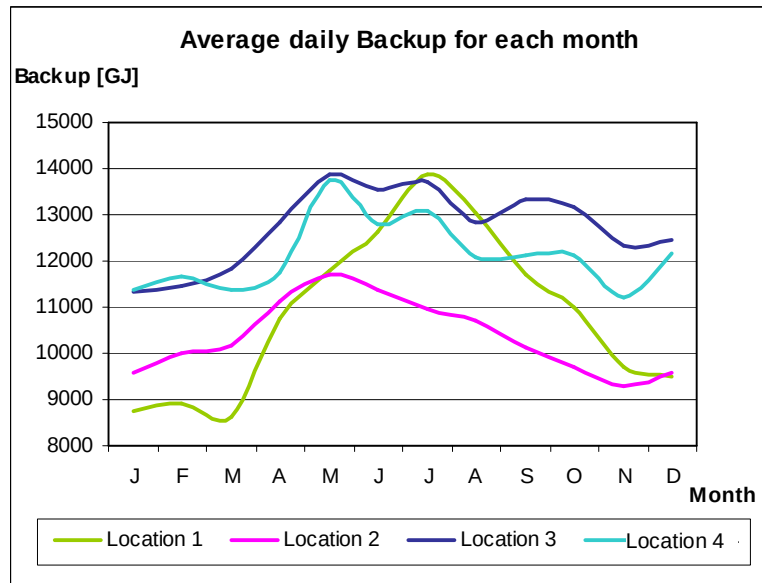


Figure 7-5: Average daily backup for each month.

The second best location (in total backup requirement) is location 1 but it presents a high variability during the year.

Location 2 has the lowest backup requirement and is predicted to be the location with the highest NE due to the influence of backup in lifecycle power plant energy requirements.

7.5 Fuel cycle energy requirement

Total energy requirement for the fuel cycle is proportional to the lifecycle backup requirement and therefore it is different for each location (as described in section 6.7.3). Results for power plant operation during sunlight hours are different from results obtained for continuous operation as shown in Tables 7-4 and 7-5.

Table 7-4: Fuel cycle energy requirements, 12 hours of operation.

Location	1	2	3	4
Exploration	682	646	815	773
Production, storage & processing	7.069	6.692	8.452	8.007
Delivery	3.174	1.918	4.030	3.654
Fuel Cycle ER (TJ)	10.926	9.256	13.299	12.435

Fuel cycle energy requirements include energy costs of exploration, production, storage, processing and delivery of the fuel. In both scenarios (sunlight hours and continuous operation) the highest fuel cycle ER is for location 2, and the lowest is for location 3.

First conclusion is that Fuel cycle ER does not depend on latitude but is highly dependent on radiation levels.

Table 7-5: Fuel cycle energy requirements, 24 hours of operation.

Location	1	2	3	4
Exploration	1.851	1.815	1.985	1.942
Production, storage & processing	19.183	18.805	20.566	20.121
Delivery	6.439	5.184	7.296	6.919
Fuel Cycle ER (TJ)	27.474	25.805	29.847	28.984

As shown in figure 7-6 and 7-7, production, storage and processing of fossil fuel is the most energy intensive process for each location. Location 2 displays the lowest energy requirement for production and delivery in both scenarios.

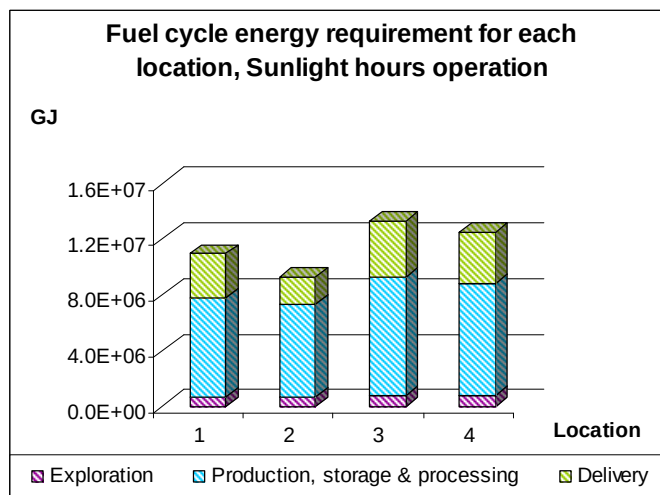


Figure 7-6: Composition of fuel cycle energy requirements for each location, Sunlight hours operation.

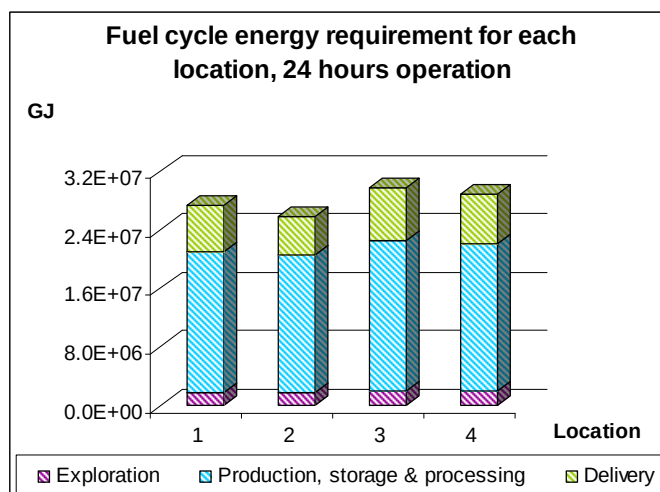


Figure 7-7: Composition of fuel cycle energy requirements for each location, 24 hours operation.

When values of total fuel cycle energy requirement for each location are compared as displayed in figure 7-8 results for continuous operation fuel cycle ER for all locations are more than two times the fuel cycle ER for sunlight hours only operation mode.

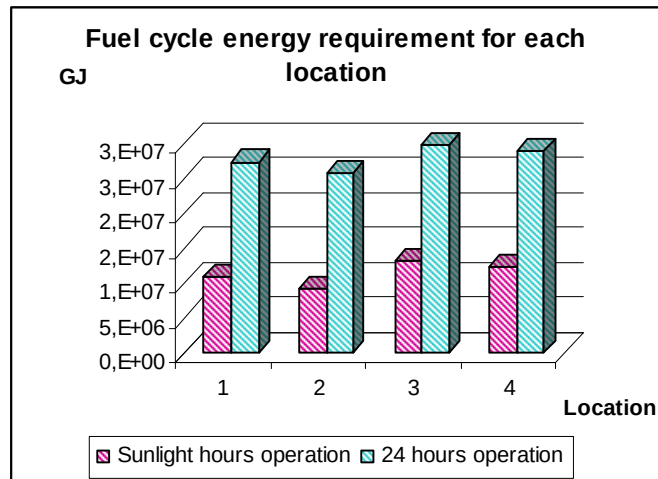


Figure 7-8: Fuel cycle energy requirement for each location, comparison between sunlight hours operation and 24 hours operation.

Delivery energy requirement is higher for location 3 in both scenarios and reaches 30% (detail in Figure 7-9) of fuel cycle energy requirement for sunlight hours operation. This is due to the large pipeline required to deliver fossil fuel to the location (details in section 7.5.1).

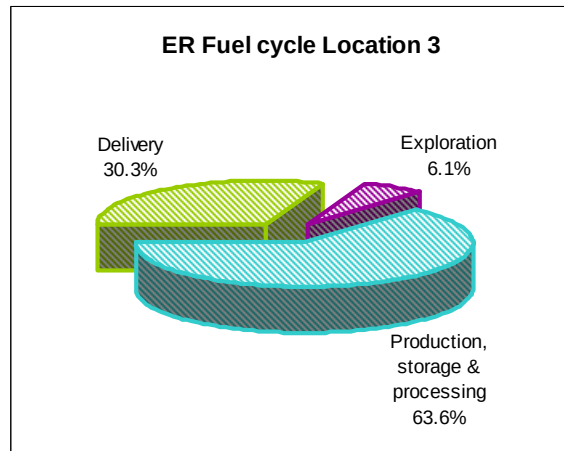


Figure 7-9: Composition of fuel cycle energy requirement for location 3, sunlight hours operation.

Details of ER estimations for components of the fuel cycle are described in following sections.

7.5.1 Delivery

As explained before, energy costs of fuel delivery take account of additional transport pipeline construction (materials and installation energy costs), transport fuel losses and energy cost of adding compressor stations (if needed). Only transport fuel losses are different for each scenario because it is a function of lifetime fuel delivered to the plant. Results for pipeline materials energy cost for each location are shown in Table 7-6.

Table 7-6: Pipeline materials energy cost for each location.

Location	Pipe Diameter (inches)	Emergy (GJ/mile)	Transport pipeline requirement (miles)	Total energy (GJ)
1	20	4.477	181,2	811.232
2	20	4.477	15,7	70.288
3	16	3.592	336,5	1.141.408
4	24	5.361	185,4	993.929

Results of energy required for pipeline construction obtained with I/O Emergy (GEMIS, 2008) in function of pipe diameter are shown in Table 7-7.

Table 7-7: Pipeline construction energy cost for each location.

Location	Pipe Diameter (inches)	Emergy (GJ/mile)	Transport pipeline requirement (miles)	Total energy (GJ)
1	20	2.496	181,2	452.275
2	20	2.496	15,7	39.187
3	16	1.800	336,5	605.700
4	24	2.677	185,4	496.315

Data for material requirement and fabrication energy costs for a standard NG compressor, required for NG delivery are obtained from GEMIS database (GEMIS, 2008), obtaining a total energy cost of 5309 GJ for the compressor (as shown in Table 7-8). Additional compressor station components were not considered.

Table 7-8: Compressor energy costs.

Compressor energy cost	Tones	Energy (GJ)
Steel	25	1.327
cement	65	499
Construction energy requirement		3.483
ER Compressor (GJ)		5.309

Transmission losses are obtained from lifetime fuel delivery to the plant and the production/delivery rate. Results are very different for both scenarios, because of the increase in fuel delivery requirements for the PTC plant is more than two times higher for a 24 hour operation as shown in Tables 7-9 and 7-10.

Table 7-9: Transport fuel losses for each location, sunlight hour operation.

Location	1	2	3	4
Lifetime Fuel Delivery to plant (TJ)	104.133	98.577	124.506	117.960
(1 - Relation p/d)	0,0183	0,0183	0,0183	0,0183
Transport fuel losses (TJ)	1.905	1.803	2.278	2.158

Table 7-10: Transport fuel losses for each location, 24 hours operation.

Location	1	2	3	4
Lifetime Fuel Delivery to plant (TJ)	282.575	277.019	302.948	296.402
Transport fuel losses (TJ)	5.171	5.069	5.543	5.424

Finally, delivery energy requirements for each location are summarized in Table 7-11. As shown, transport fuel losses are the highest costs in both scenarios.

Table 7-11: Fuel delivery ER for each location.

Location	1	2	3	4
Pipeline Material	811.232	70.288	1.141.408	993.929
Pipeline Installation	452.275	39.187	605.700	496.315
Compressor station	5.309	5.309	5.309	5.309
Transport Fuel losses (12 h)	1.905.650	1.803.975	2.278.476	2.158.684
ER Delivery 12 h operation (GJ)	3.174.467	1.918.761	4.030.894	3.654.239
Transport Fuel losses (24 h)	5.171.124	5.069.450	5.543.950	5.424.158
ER Delivery 24 h operation (GJ)	6.439.941	5.184.235	7.296.367	6.919.713

7.5.2 Production, storage and processing

Total energy required for NG production, storage and processing (PS&P) is obtained as described in section 3.2.4. Details are displayed in Table 7-12.

Table 7-12: PS&P ER for each location.

Location	1	2	3	4
Sunlight hours operation scenario				
Lifetime Fuel Delivery to plant (TJ)	104.133	98.577	124.506	117.960
Relation p/d	1,0183	1,0183	1,0183	1,0183
Lifetime NG Required production (TJ)	106.039	100.381	126.785	120.119
1/EROI	1/15	1/15	1/15	1/15
ER PS&P (TJ)	7.069	6.692	8.452	8.007
24 hours operation scenario				
Lifetime Fuel Delivery to plant (TJ)	282.575	277.019	302.948	296.402
Lifetime NG Required production (TJ)	287.746	282.088	308.492	301.826
ER PS&P (TJ)	19.183	18.805	20.566	20.121
Increase percentage	171%	181%	143%	151%

As shown the increase in production, storage and processing energy requirement for 24 hour operation mode is proportional to the backup requirement for each location.

7.5.3 Exploration

Total energy required for NG exploration for an exploration cost of 0,006436 GJ/GJ produced is displayed in Table 7-13. Again, a higher ER in both scenarios is for locations with higher backup utilization. Also, an increase of exploration ER is proportional to the increase in lifetime NG required production.

Table 7-13: Exploration energy requirement for each location.

Location	1	2	3	4
Sunlight hours operation scenario				
Lifetime NG Required production (TJ)	106.039	100.381	126.785	120.119
ER Exploration (TJ)	682	646	815	773
24 hours operation scenario				
Lifetime NG Required production (TJ)	287.746	282.088	308.492	301.826
ER Exploration (TJ)	1.851	1.815	1.985	1.942

7.6 Component manufacturing and plant construction phase

For this study, it is assumed that plant construction will take three years before start-up. Further, all structures and equipment assembly took place in this time period. Energy requirement of the component manufacturing and plant construction phase (ER_{PC}) of plant lifecycle includes material, equipment, construction and workers energy costs, and are calculated as described in section 3. Subtotal results (in Table 7-14) are the same for all locations but ER associated with material transport is not, as described in Table 7-15, because differences in the distances to the final destination. Costs for plant equipment, solar field construction, and equipment assembly are very difficult to estimate. Even so, this study used data available in an economic analysis for a 100MW CSP plant (Schwer and Riddel, 2004) performed by NREL (National Renewable Energy Laboratory).

As shown in Table 7-14, solar field material requirements are the highest energy costs in this stage of the plant lifecycle. Parts of these costs are recoverable in the decommissioning stage of this plant that includes material recycling. This is due to the energy intensive process required to obtain pure materials. As expected, ER related to human labor were nearly irrelevant as it is less than 0.06% of the energy costs. Direct jobs created in this phase were approximately 130 (Sargent and Lundy, 2003) and

indirect job creation (not included in this study) are more than 1500 (Schwer and Riddel, 2004).

Table 7-14: Component manufacturing and plant construction ER.

Solar field materials (1400 collectors)	Volume (m3)	ton	Energy (GJ)
Glass (receiver)	149,39	328,65	8.245
Steel (receiver)	202,96	1.593,25	84.601
Mirror (concentrator)	1.599,36	3.518,59	88.281
Steel (structure)	1.994,03	15.653,10	406.041
ER Solar field Materials			587.170
Plant Equipment	Cost (\$Thou)	Energy intensity (GJ/\$Thou)	Energy (GJ)
Electric Power Generation system	24.371	6,49	158.168
BOP	9.140	2,43	22.210
Steam generator	8.570	8,66	74.216
ER Equipment			254.594
Construction	Cost (\$Thou)	Energy intensity (GJ/Thou\$)	Energy (GJ)
Solar field & Equipment assembly	32.911	1,93	63.518
ER Construction			63.518
Workers	Quantity	Energy/hour-worker (kJ/h)	Energy (GJ)
Lifetime hours/worker (hrs)	2.700		
Engineers & administration	28	796	60
Workers	100	1.804	487
ER Workers	128		547
Subtotal ER Construction & Materials			905.829

Table 7-15: Energy requirement for materials transport.

Mirror transport from US				
Location	1	2	3	4
Mirror (ton)	3.519	3.519	3.519	3.519
Nautical Miles	3.963	4.108	4.108	4.108
Ship Consumption	18.281	18.950	18.950	18.950
km	138	173	612	922
Truck consumption	475	599	2.114	3.181
Subtotal (GJ)	18.756	19.548	21.064	22.131
Receiver transport from US				
Location	1	2	3	4
Tons (Glass and Steel)	1.922	1.922	1.922	1.922
Nautical Miles	3.963	4.108	4.108	4.108
Ship Consumption	9.985	10.351	10.351	10.351
km	138	173	612	922
Truck consumption	260	327	1.155	1.738
Subtotal (GJ)	10.245	10.677	11.505	12.088
Steel transport from Huachipato				
Location	1	2	3	4
Steel (ton)	15.653	15.653	15.653	15.653
km	2.510	2.053	1.268	958
Truck consumption (MJ/km-ton)	4.732	3.871	2.390	1.807
Subtotal (GJ)	4.732	3.871	2.390	1.807
Total Materials transport ER	33.732	34.097	34.959	36.026

Only transport energy related with solar field materials is accounted, because there was no data for other plant equipment materials inventory. Anyway, solar field represents more than 60% of the PTC plant costs (Schwer and Riddel, 2004), and material requirements are usually related to real costs. Collector receiver and mirrors are supposed to be fabricated in the US due to the uniqueness of the equipment and the high precision mirrors required. In a future Chilean production of these products could be analyzed. It is assumed that all steel will be obtained from the Huachipato steel factory in southern Chile.

Table 7-16: ER for Component manufacturing and plant construction phase.

Location	1	2	3	4
Construction & Materials	905.829	905.829	905.829	905.829
Materials transport ER	33.732	34.097	34.959	36.026
Total C&M ER (GJ)	939.561	939.926	940.788	941.855

Total ER for component manufacturing and plant construction phase (ER_{PC}) is calculated in Table 7-16. Material transport ER is less than 5% for this phase but if data for more components becomes available this value may reach higher participation. In this phase Location 1 presents lower energy costs due to its proximity to the Iquique port. As seen, differences between locations are small, compared with other lifecycle phases.

7.7 Plant operation and maintenance phase

A typical parabolic trough collector facility operates for 30 years. Plant operation and maintenance (O&M) energy requirements (ER_{PO}) are low in comparison to other plant costs, because the principal input to the plant in this phase is fuel, which is accounted for separately. Costs of operation and maintenance (Schwer and Riddel, 2004) include equipment replacement and repair and solar field cleaning. Permanent jobs required

during plant O&M phase of the plant were approximately 82, significantly less than during the construction phase. As seen in table 7-17, ER for O&M phase of the plant, excluding energy requirement of fuels, for all locations is about 93 TJ.

Table 7-17: Energy requirement for Operation and Maintenance phase.

Workers	Quantity	Energy/hour/ worker (kJ/h)	Energy (GJ)
Hours/worker (hrs)	54.000		
Administrative	8	796	343
Operations	19	796	816
PB Maintenance	12	1.478	957
SF Maintenance	43	1.478	3.431
Workers ER	82		5.550
Operation and Maintenance	Cost (\$Thous)	Energy Intensity (GJ/\$Thous)	Energy (GJ)
O & M	8.282	10,6	87.789
O&M ER			93.339

7.8 Decommissioning, materials recycling and refurbishment

Decommissioning, material recycling and refurbishment energy requirement (ER_{DRR}) of the plant takes one and a half year to be completed. It is assumed that labor required in this phase is equal to that used in the construction phase. It is considered that the energy cost of dismantling the plant is equal to the cost of solar field construction and equipment assembly, described in chapter 6. Also, it was considered that 70% of the steel can be recovered with a recovery rate of 90%. Glass recovery is assumed to be 40%. Cost of terrain refurbishment is assumed to be similar to the data for a California installation of PTC (California energy commission, 2003). As shown in Table 7-18,

energy recovered from materials is more than energy costs for this plant phase and consequently energy requirement obtained is displayed as negative.

Table 7-18: Decommissioning, material recycling and refurbishment ER.

Workers	Quantity	Energy/hour/ worker (kJ/h)	Energy (GJ)
Lifetime hours/worker (hrs)	2.700		
Engineers & administration	28	796	60
Dismantling Workers	100	1.804	487
ER Workers	128		547
Materials recuperation	%	Ton	Energy (GJ)
Steel	0,63	17.246,35	281.843
Glass	0,40	328,65	3.298
ER Materials recuperation			-285.141
Others	Cost (\$Thou)	Energy Intensity (GJ/\$Thou)	Energy (GJ)
Dismantling			63.518
Terrain Refurbishment	4.081	10,6	43.258
Decommission, material recycling and refurbishment ER			-177.817

7.9 Net energy for each location

Energy requirements of each phase of the plant lifecycle plus fuel cycle requirements are added to perform an energy balance during plant lifecycle (almost 35 years). A simplified gross energy requirement is calculated that excludes components and processes for which accurate information is not available or it is difficult to estimate

with the process energy analysis method. Results for each location, in both scenarios (12 and 24 hours operation) were analyzed.

Details of energy balance of the plant for sunlight hours operation mode are displayed in Table 7-19. As shown, for the analyzed design solar fraction is lower than 50% but NE obtained for the PTC plant is positive for all locations. Then, for this operation mode all locations are sources of energy during them lifecycles.

Table 7-19: Energy balance and Net energy for sunlight hours operation mode.

Location	Loc 1	Loc 2	Loc 3	Loc 4
Backup fraction (yearly mean) %	0,58	0,55	0,70	0,66
Direct fuel Energy Input TJ	104.133	98.577	124.506	117.960
Fuel Cycle TJ	10.926	9.256	13.299	12.435
Plant Construction and Materials TJ	939	939	940	941
Plant operation and Maintenance TJ	93	93	93	93
Plant decommission and Land Reclamation TJ	-177	-177	-177	-177
Life cycle energy Input TJ	11.781	10.112	14.155	13.292
Life cycle energy Output TJ	56.291	56.291	56.291	56.291
NE (TJ)	44.510	46.179	42.136	42.999
NE (GWh)	12.364	12.827	11.704	11.944

The most important component of energy input is the energy requirement of the fuel cycle, which corresponds to more than 90% of the input energy costs, as displayed in Figure 7-10, for location 1. Then, for lower backup fractions it is expected to obtain a higher net energy.

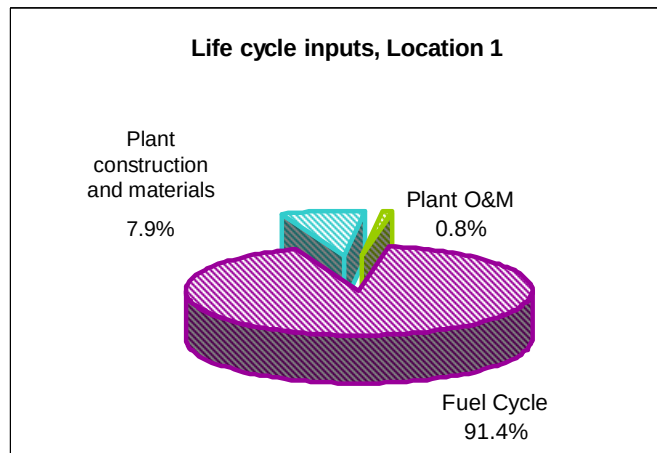


Figure 7-10: Life cycle inputs for Location 1, in 12 hours operation mode.

For the 24 hour operation mode, solar fraction is lower than 30% (Table 7-20) and the total energy obtained from the plant as electrical output is doubled.

Table 7-20: Energy balance and Net energy for 24 hours operation mode.

Location	Loc 1	Loc 2	Loc 3	Loc 4
Backup fraction (yearly mean) %	0,79	0,78	0,85	0,83
Direct fuel Energy Input TJ	282.575	277.019	302.948	296.402
Fuel Cycle TJ	27.474	25.805	29.847	28.984
Plant Construction and Materials TJ	939	939	940	941
Plant operation and Maintenance TJ	93	93	93	93
Plant decommission and Land Reclamation TJ	-177	-177	-177	-177
Life cycle energy Input TJ	28.330	26.661	30.704	29.841
Life cycle energy Output TJ	112.583	112.583	112.583	112.583
NE (TJ)	84.253	85.922	81.879	82.742
NE (GWh)	23.403	23.867	22.744	22.983

As in the sunlight hours operation mode, NE obtained for the PTC plant is positive for all locations, and they are sources of energy. As shown in Figure 7-11, NE for the 24 hour operation mode is approximately two times NE for sunlight hours mode, due to the increase of operation time, and consequently backup requirements.

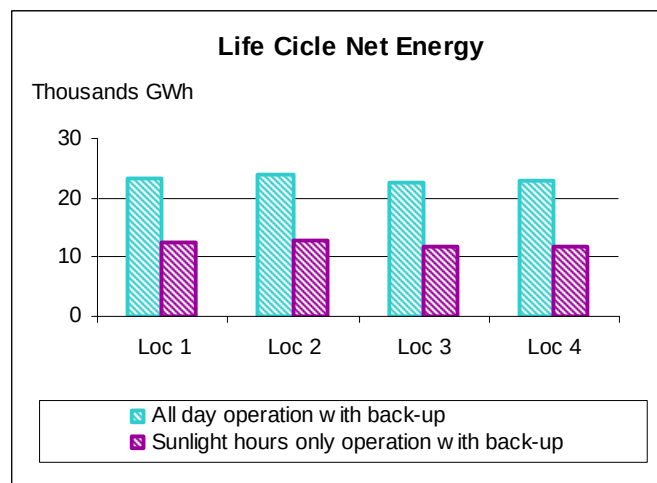


Figure 7-11: Net energy for all locations, in both operation modes.

7.10 Sustainability indicators: EROI and Energy payback time

In this thesis, sustainability indicators related to energy resource consumption have been estimated for each location in both operating modes, in order to determine effective capacity of the system to generate useful energy (energy source system) and ensure that the system does not contribute to energy resources depletion, assuring that the same (or more) energy than what is required to support the system (total energy requirements) is going to be available to future generations.

7.10.1 Energy return over investment, EROI

EROI for each location, in both operation modes is calculated. As shown in Table 7-21, for different locations and operating modes, PTC plant EROI is higher than 1. Then, PTC plant becomes an energy source in all locations analyzed. As expected, EROI results are proportional to solar fraction.

EROI for a real natural gas plant of 4.09 (Meier, 2002) is used as a reference value, considering that a Hybrid PTC power plant is at the limit (when fossil fuel backup fraction is 1) a natural gas plant. Locations 1, 2 and 4 for sunlight hours operation mode are a more convenient alternative than the natural gas plant, from the energy generation point of view without considering additional benefits related with emissions reduction generated by the solar alternative.

Table 7-21: EROI for all locations, in both operation modes.

EROI	Loc 1	Loc 2	Loc 3	Loc 4
Sunlight hours operation	4,778	5,567	3,977	4,235
24 hours operation	3,974	4,223	3,667	3,773

For a 24 hour operation mode only location 2 is a better energy generation alternative than the NG plant, from the energy consumption point of view.

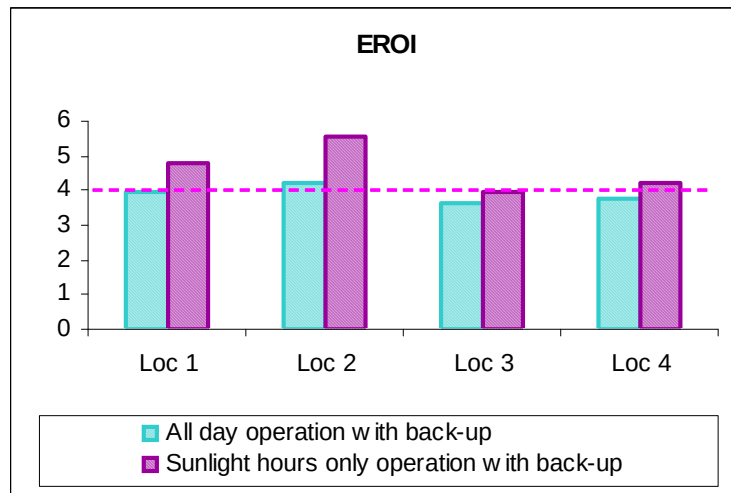


Figure 7-12: Net energy for all locations, in both operation modes compared with a traditional NG power plant.

In Figure 7-13 variation of net energy as function of the backup fraction and EROI for all analyzed alternatives is displayed. The only difference between the two operating modes (sunlight vs. continuous operation) is the time of generation and consequently the use of fossil fuel. That means the plant in continuous operation mode is the same plant but needs a higher backup requirement than the plant in sunlight hours operating mode. In the figure, two bubbles are displayed for each location that represents different values of backup fractions. The size of the circles represents the respective NE for each point. For higher backup fractions more net energy is obtained but energy return rate decrease substantially. Then, 24 hour operating mode is not the best solution from the energy resources utilization point of view because it provides less energy output per unit of energy input.

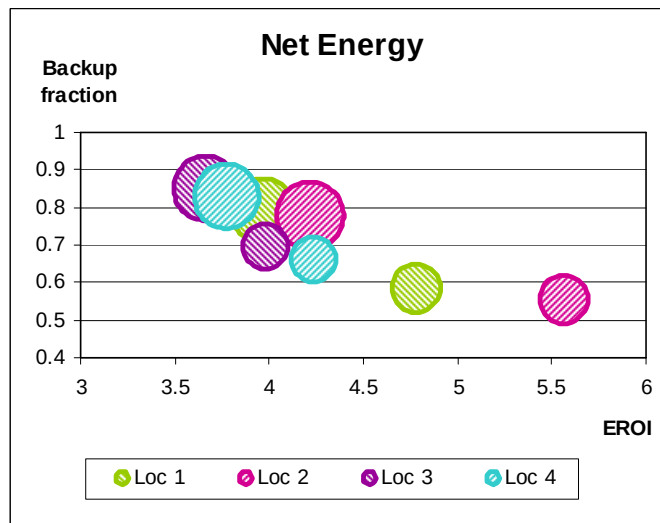


Figure 7-13: Net energy for all locations, as function of the Backup fraction and EROI.

7.10.2 Energy payback time (EPT)

Energy payback time is different for each location reaching values between 5.4 and 7.6 years for sunlight only operation and between 7.1 and 8.2 years for continuous operation. An EPT of 7 means that energy generated from year 7 is energy gain from the plant. High materials energy cost in the plant's construction phase increase the EPT, but energy recovered from material recycling is not accounted for until the first year of the plant's decommissioning. As seen in Table 7-22, energy payback time for location 2 has the lowest values. This means that energy invested in the power plant at location 2 is recovered earlier at this location. Using the EPT value as a selection tool location 2 is again the most attractive location.

Table 7-22: EPT for all locations, in both operation modes.

EPT (years)	Loc 1	Loc 2	Loc 3	Loc 4
Continuous operation	7.6	7.1	8.2	8.0
Sunlight-hours only Operation	6.3	5.4	7.6	7.1

There is a limit for EPT values, determined by a line with a slope of 1, called energy carrier limit (ECL) for which values in the line have life cycle NE of zero and becomes an energy carrier. For points above the ECL the system becomes an energy sink, and for points below the ECL line the systems becomes an energy source, as shown in figure 7-14. EPT for both scenarios is a dynamic function of the number of operating years, as can be seen in Figures 7-15 and 7-16. This means that with each passing year that the plant generates energy the fossil fuel consumption increases and therefore more years are needed in order to balance the energy account.

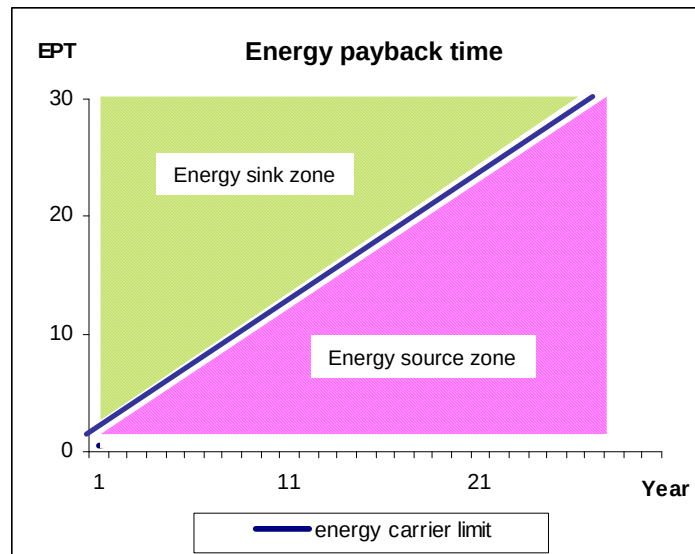


Figure 7-14: EPT for all locations, as function of the operation years, for sunlight hours only operation.

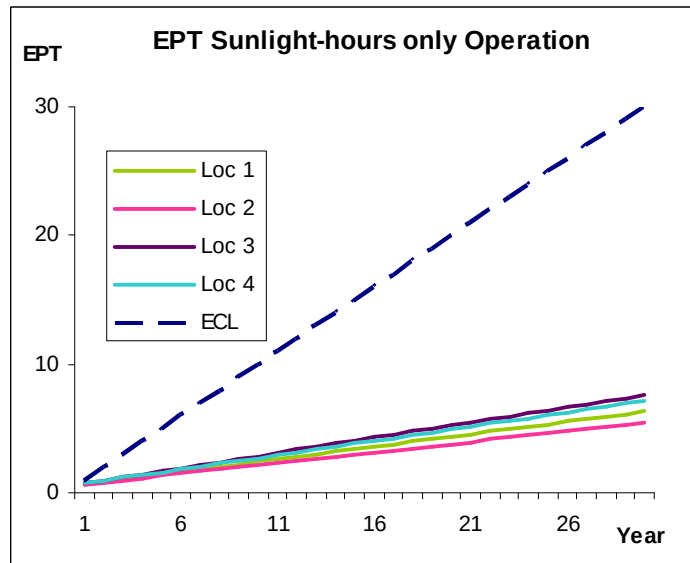


Figure 7-15: EPT for all locations, as function of the operation years, for sunlight hours only operation.

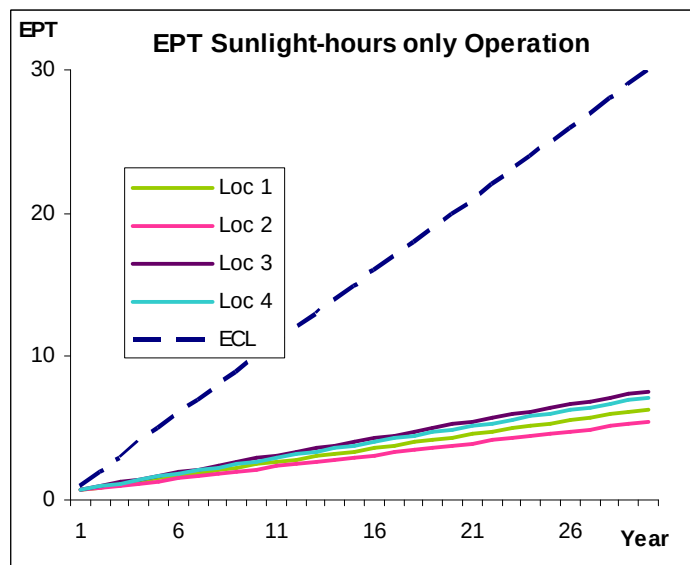


Figure 7-16: EPT for all locations, as function of the operation years, for continuous operation.

The EPT line for all locations in both operating modes is below the ESL line indicating that the power plants are a source of energy. The EPT line determines a relation between operating years and EPT for each location (Table 7-23).

Table 7-23: EPT (y) as function of operation years (x).

EPT (years)	Continuous operation	Sunlight-hours only Operation
Loc 1	$y = 0,24x + 0,25$	$y = 0,19x + 0,5$
Loc 2	$y = 0,22x + 0,25$	$y = 0,16x + 0,5$
Loc 3	$y = 0,26x + 0,25$	$y = 0,23x + 0,5$
Loc 4	$y = 0,25x + 0,25$	$y = 0,22x + 0,5$

Also, a relationship between EPT (at final of the operational years) and EROI exists (as shown in figure 7-17), where for each location and for both operating modes, values of EROI vs. values of EPT are displayed. The relationship has a lineal tendency with an R^2 higher than 99% in both operating modes. For the continuous operation mode the relationship between both indicators is described by the function:

$$EPT_{co} = -1,93 \cdot EROI + 15,2 \quad (7.1)$$

And for sunlight hours operating mode, the relationship is described by:

$$EPT_{so} = -1,34 \cdot EROI + 12,8 \quad (7.2)$$

Then, if EROI for the plant lifecycle is obtained, EPT can be simply calculated.

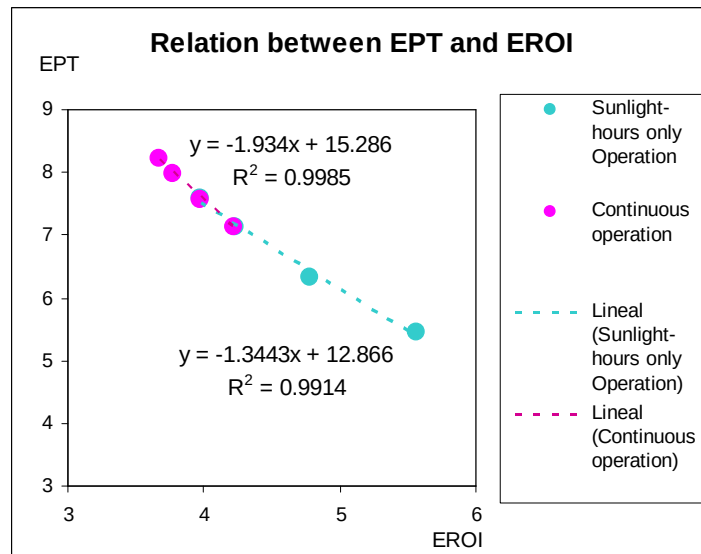


Figure 7-17: EPT for all locations, as function of the operation years, for continuous operation.

8. CONCLUSIONS

Environmental and depletion issues related to the extensive use of fossil fuels in the last decades has created a global concern and interest to reduce its use and to encourage a transition to cleaner energy sources, including renewable energies, to achieve sustainable development. Taking into consideration the significance of achieving sustainable development, resources conservation becomes an important goal in order to ensure that energy invested for current generations is going to be available for future generations, especially energy resources, considering that energy supports development. By performing NEA to each new energy generating system to be developed in the future the effective energy produced by the system is obtained. Of all the renewables, solar energy appears as an excellent alternative to for development in Chile, mainly because the north of the country presents high radiation levels and adequate terrain availability. In this context it is interesting to perform a NEA to this alternative before its development. As lifecycle energy requirements of power plants are dissimilar when they are installed in different locations, the present thesis attempts to present a selection methodology to determine optimal power plant locations, based on a NEA and energy sustainability indicators.

To select the most appropriate alternative among solar energy technologies a full investigation of CSP plants was undertaken. It is, therefore, concluded that the most advisable CSP technology, based on current development trends and actual electricity generation costs, is the parabolic trough collector type. In order to operate this PTC plant continuously, a fossil fuel backup system is included making the plant a hybrid power plant. Taking this selection into consideration, a 100 MW hybrid parabolic trough collector power plant of the DSG type in four different locations throughout northern Chile are analyzed, in order to calculate its NE. DSG model was selected because it is made up of a reduced number of components that reduces costs and increases global efficiencies while reducing risks related to the use of others working fluids. Fluid properties in the steam cycle are fixed and fluid is heated by solar radiation (in the solar

field) and by a natural gas heater to reach turbine inlet properties. How much of the heat is added by the heater and how much by the solar field is determined by solar radiation levels.

Since the higher energy input component of plant lifecycle is related to the energy required by the fossil fuel cycle (reaching more than 90% of total energy inputs to the system), a model of the plant in EES is performed, in order to obtain accurate data of yearly backup required for the available radiation levels at each location. Data of solar radiation in Chile is available in monthly means but to model the plant then an hourly beam radiation is required.

Two alternatives to obtain hourly beam radiation from monthly means were used as input in the EES model for one location to obtain yearly backup, and the results compared. The first alternative analyzed considers a month with identical days in which every day looks like an average day; and second alternative was to fabricate an artificial month using monthly mean data. As expected, the first alternative gives underestimations of utilizable energy, translating into an energy backup requirement higher than 20% to a 32% of the values obtained modeling the artificial month. As a conclusion, an artificial month must be constructed for each location to obtain beam radiation for each hour of the year to accurately predict the yearly fossil fuel backup requirement. This process requires a large investment in time for each model. Then, hourly beam radiation data for each hour of the year is obtained, and used as an input to the solar field model obtaining yearly backup requirements.

The EES model estimates backup requirement for sunlight hours for each hour of the artificial month and adds these values to obtain monthly backup. Results displayed in Figure 8-1 show a monthly backup requirement between 70% and 40% for all locations. Location 2 has the lowest backup requirement during most months of the year and is also the location with lowest yearly backup requirement. These results added to the fact that location 2 also presents the lowest variations during the year indicate that this is the

most appropriate site to build the plant. Also, it is obtained that location 3 has the higher backup requirement and then is the less recommended location to install the PTC plant.

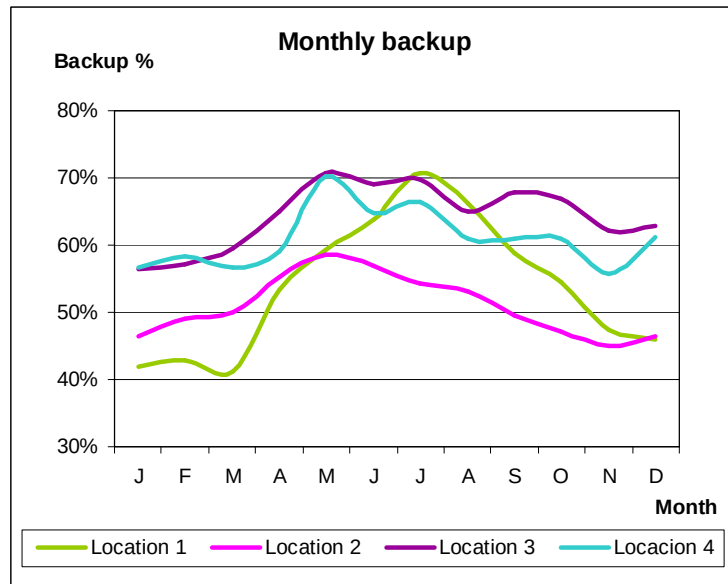


Figure 8-1: Monthly backup, in percentage for all locations.

From NEA results it is obtained that the most important component of plant lifecycle is energy requirement of the fuel cycle. More than 90% of the energy inputs of the system are related to this item mainly because of the high energy cost of production, storage and processing of the natural gas required to support the plant's operation. Energy requirements for the fuel cycle are proportional to the backup requirements and radiation levels validating the need to develop a model of the plant in EES to obtain accurate data of backup required because the value differences can be decisive in the decision making process. Other expensive energy processes of the plant lifecycle are solar field materials and plant equipment related to the high cost of steel components.

The results conclude that the hybrid PTC plants are a net energy source for all four locations studied with a positive NE near 43 thousand TJ for sunlight hours operation and near 83 thousand TJ for continuous operating mode. Then, it is concluded that PTC

power plant from the energy resource depletion point of view, contribute to the sustainable development demonstrating that the technology is not only a solution to reduce GHG emissions but also presents an ideal alternative as an energy source without compromising energy resources depletion thus ensuring resources to future generations.

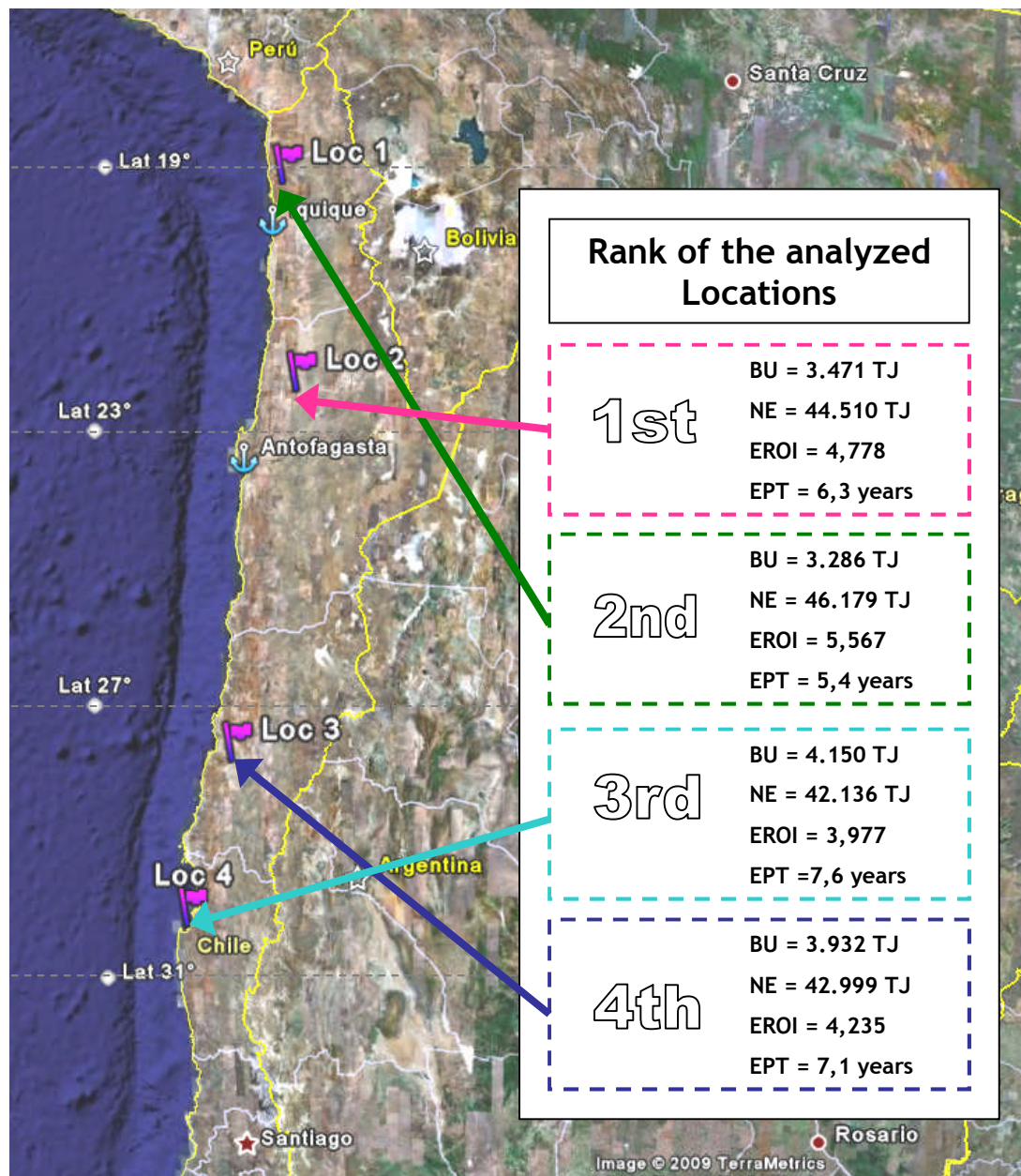


Figure 8-2: Rank of the analyzed locations for sunlight operation mode.

To compare energy generation efficiency of these plants with other alternatives in order to select the most convenient from an energy point of view an EROI indicator is used. All PTC plants analyzed in this study were compared with a traditional NG plant with an EROI of 4.09. It has been obtained that for sunlight hours only operation mode, location 1, 2 and 4 are more convenient because the investment of 1 J of energy have a higher return for these installations. In the continuous operation mode, CSP plants in location 1, 3 and 4 become less efficient than traditional NG plant and only the CSP plant in location 2 maintain a higher EROI. The best location to develop a PTC plant in energy return terms is location 2 that means that resource investment in this location generates additional gains than other alternatives. In conclusion, using EROI indicators, to develop a PTC power plant for sunlight operation in location 3 and for continuous operation in locations 1, 3 and 4 is not recommended because energy recovered is lower than that from a traditional natural gas power plant, as shown in Figure 8-3. However, if environmental issues are added to the analysis it is expected that the PTC power plant will be always a better alternative over the traditional NG alternative. It is then concluded that for higher backup fractions more net energy is obtained but energy return rate decreases substantially.

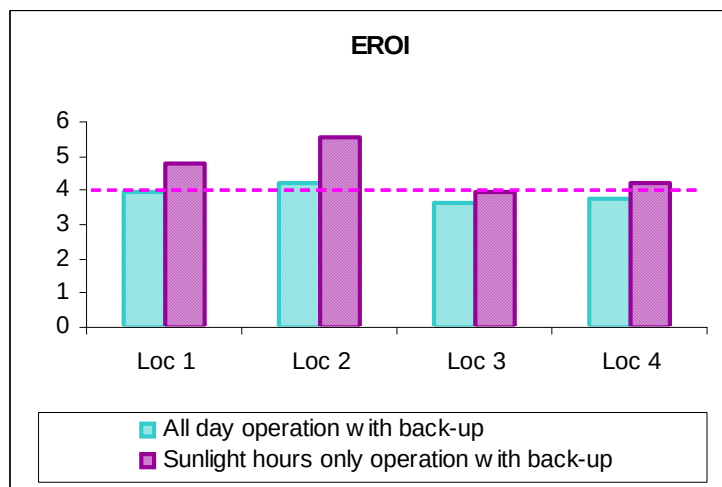


Figure 8-3: Net energy for all locations, in both operation modes compared with a traditional NG power plant.

Energy payback time obtained for the plants results in a dynamic quantity, function of the number of operating years and the EROI, with values between 5.4 and 7.6 years for sunlight hours only operation and between 7.1 and 8.2 years for continuous operation. This means that energy generated from the year obtained as the calculation of the EROI is energy gain from the plant. During plant lifecycle, EPT for the plant are under the energy carrier limit, in the energy source zone. This means that if the power plant generation ends in any year before its 30 years of expected operation, it still produces a net energy gain during the interrupted lifecycle. Using EPT as a selection indicator the best alternative in both operating modes is again location 2 because it recovers energy investment before than the other three alternatives.

Finally, the present study concludes that within the four locations analyzed using NEA, from an energy resource consumption point of view, location 2 is the most adequate location to setup a technology construction project and operate a hybrid PTC power plant. From the analysis it is concluded that the high energy consuming process in the plant lifecycle is fossil fuel production, storage and processing, reaching more than 50% of total energy requirements. Then, replacement or improvement of these processes may be an additional support to reducing energy consumption.

The analysis presented in this thesis can be used to estimate plant performance and sustainability attributes of concentrated solar power plants in cases where only monthly means of radiation data is available.

Also, the thermodynamic model of the plant developed in EES can be used as a tool to evaluate backup requirements of the plant in any location of interest, providing information related to impacts of changing plant configuration or components on yearly backup requirement and consequently in energy effective generation.

The methodology developed in this work, to account for a plant's lifecycle energy requirements can be applied to different energy generation technologies, in order to

obtain the NE and determine system quality as an energy source, carrier or sink of energy for the implementation of the plant in different locations.

It is estimated that the net energy analysis is a useful tool for determining under which conditions a CSP plant becomes a net energy source, and thus can be utilized in order to define geographical locations and operating conditions where they can be considered renewable energy sources, in order to help the decision-making process needed for implementing CSP technologies as part of an energy security strategy. Energy attributes obtained from the NEA, are valuable data to compare between different energy generation options and to define the most convenient alternative (or mix of alternatives) for each location.

It is concluded that CSP can be one of the contributors to the country's energy independence and security of supply, reduction of GHG emissions and from a global point of view to sustainable development.

Finally, this thesis wishes to open a discussion about the importance of analyzing the effects of actual generation decisions on energy resource depletion, taking into consideration not only environmental and economic effects of the new projects but also energy requirements in order to ensure future generations energy resources availability and achieve a sustainable development.

8.1 Recommendations for future works

An improvement to the analysis presented in this thesis could be made if real data of solar radiation for each hour of the year is obtained and used instead the artificial month to model plant performance.

The possibility of local production of some components of the plant (like glass) can reduce energy requirements related with materials transportation. In this case, energy intensity for Chilean fabrication must be obtained.

As the energy requirement of the fuel cycle is more than 90% of the systems inputs a plant improvement can be achieved with the implementation of a heat energy storage system that extends the energy generation period without raising fossil fuel consumption.

An additional recommendation for future analysis of hybrid power plants in Chile is to consider a backup of liquefied natural gas from Mejillones international terminal instead natural gas from Argentina, in order to reduce the negative effects of instability in imports from this country.

Also, for future studies of NEA, GHG emissions analysis can be added converting energy data into emissions data. Then, a more complete perspective can be obtained to select more convenient locations to develop the PTC plants.

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