Geothermal projects: Exploration, Drilling, Plant, Exploitation, Operation & Maintenance

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Geothermal Innovation & Sustainability
Enel Green Power
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The Geothermal Value Chain
Integrated business model – Striving for Excellence

Centennial experience (since 1904) in geothermal electricity generation and fluid use

Project Development/Finance
- Acquire land rights
- Risk evaluation depending on country and technology
- Transmission System Access
- Power sales contract negotiation
- Acquisition of concessions

Exploration & Drilling
- Best practice in drilling target identification
- Geological Model and reservoir evaluation
- Predictive methodology for exploration of deep geo resources
- Skills and equipment to drill vertical and deviated geothermal wells
- Innovative flow testing programs to forecast well performance

Plant design/construction
- Well proven concept design in diverse technologies: dry steam, flash and binary
- Provide an environment of competition in equipment procurement and construction
- Standardize where possible

Plant operation
- Fully developed internal safety and operations procedures
- Optimized geo-resource management (reservoir and power plant) for sustainable exploitation
- In house maintenance and repair capability
- Plants remotely monitored and controlled from a centralized location

R&D
- Low Enthalpy Innovative Geothermal Plants
- Developing hybrid system
- Plant improvement: acid gas components abatement
- Improved efficiency and flexibility

EGP growth in traditional high temperature resources and also in binary technology
The Geothermal Value Chain
Prefeasibility, feasibility and project development

Prefeasibility
- Country level studies to rank opportunities
- Resource assessment & evaluation referred to new opportunities:
  - green fields
  - brow fields
  - fields in exploitation

Feasibility
- Surface exploration: definition, planning, execution, interpretation
- Data analysis and interpretation to define the preliminary Geothermal Model
- Deep exploration planning
- Mining project definition
- Environmental impact studies

Construction
- Wells location and target
- Site geology
- Wells construction addressing
- Logs & tests planning

Field exploitation
- Monitoring plan definition
- Data collection and analysis
- Resource forecast
- Production recovery plan definition: make up wells, stimulation jobs, work over

The entire geothermal value chain covered
The Geothermal exploration
..a multidisciplinary approach

The joint interpretation is the key to get the most reliable geothermal model
New Geothermal project development
The assessment process

Assessment Process

- Geo resource potential assessment MWt
  - Capex curve Assessment
  - Opex overcosts assessment
  - Revenues

- Power Production Curve Forecast MWe
  - Data from exploration

TECHNICAL

ECONOMIC
New Geothermal project development

The assessment process

**Exploration Lease**

**Survey Project**
- Activities: Identification of the environmental constraints, geological surveys, geochemical surveys, geophysical surveys
- Target(s): Identification of potential reservoir
- Surface: \(10^3\) km\(^2\)
- Costs: \(3\) k$/km\(^2\)

**Exploration Project**
- Activities: Geophysical surveys

**Mining Lease**

**Development Project**
- Activities: 3D seismic surveys
- Target(s): Definition of mining
- Surface: \(10^2\) km\(^2\)
- Costs: Survey Costs \(6\) k$/km\(^2\), Drill. Costs \(150\) k$/km\(^2\)

**Exploitation / Mining**
- Activities: Production and reinjection wells, seismicity & subsidence monitoring
- Target(s): Maximizing production
- Surface: \(25\) km\(^2\)
- Costs: \(50\) k$/km\(^2\), Drill. Costs \(1500\) k$/km\(^2\)
The geothermal projects assessment is a **continuous improving process** along the project advancement. **Goals, tools and methods, reliability** of the assessments change with project development level.

### Project level

<table>
<thead>
<tr>
<th></th>
<th>Green field (surface exploration)</th>
<th>Brown field (Deep exploration)</th>
<th>Construction</th>
<th>Field in operation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knowledge</strong></td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>The production sustainability has to be monitored and revised also during the whole field operational life in order to</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td><strong>Risk</strong></td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td></td>
</tr>
</tbody>
</table>

**Increasing With Project Progressing:**

- The type and amount of available experimental data
- The type and effectiveness of appropriate tools for the assessment
- The **reliability** of the **resource assessment**
- The **accuracy** and **completeness** of the **Capex estimation**
- The technical data necessary for the final project design

**Decreasing With Project Progressing:**

- The uncertainty of the assessment
- The project risk
New Geothermal project development
The assessment process

**STATIC DATA**
- Surfaces data
- Well masterlogs
- T & P Static logs

**DYNAMIC DATA**
- Well tests

**Experimental data**
**Geo tools**
**Geo modelling output**
- Geothermal system static characteristics
  - Size and shape
  - Static T P conditions

**Resource potential assessment tools**
**Reservoir Eng. tools**
**Reservoir Eng. modelling output**
- Geothermal system dynamic behaviour under exploitation
  - T e P decline
  - Permeability characteristics

**TECHNICAL PROJECT ASSESSMENT**
- Geo resource potential MWt

**Power Production Forecast MWe**

Economic Assess.
- Capex curve (partial)
- Opex curve (partial)
- Revenues
- PPA Conditions

Power Production Forecast MWe

Reservoir Engineering Modelling

Technical Assumptions
- Power Production Forecast MWe

Geo Modelling

Reservoir Engineering Modelling

Reservoir Engineering Modelling

Geo Modelling

Geo Modelling

Geo Modelling

Geo Modelling

Geo Modelling

Geo Modelling

Geo Modelling

Geo Modelling

Geo Modelling

Geo Modelling
The geothermal prefeasibility
Country geothermal scouting – The process

The **scouting process** steps

1) **Preliminary assessment on bibliographic data**
   Data collection and data base organization
   Identifying and assessing areas of potential interest

2) **Preliminary Ranking on bibliographic data**
   Ranking criteria definition
   Application of Ranking criteria to the Atlas

3) **In field studies**
   Preliminary areas selection
   On site reconnaissance and data collections
   Data evaluation and assessment updating

4) **Ranking updating**

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OUTPUT

- Geothermal Atlas
- Preliminary Geothermal Ranking
- Atlas Updating
- Final Ranking

Step 1 | Step 2 | Step 3 | FINAL OUTPUT
The Geothermal prefeasibility
Country geothermal scouting – The Atlas

Data collection and data base organization

Bibliographic data collection
- Natural manifestations inventory
- Chemical analysis and geochemical data
- Geological, tectonic, volcanological, hydrogeological data
- Geophysical surveys

Data base organization
- GIS Data and Geo-referenced Data within GIS SYSTEM
- Not Geo-ref Data within monographic sheets framework or technical report

Identifying and assessing areas

- Locating and bounding areas on GIS base
- T Geothermometric estimation
- Preliminary conceptual modeling
- Areas size estimation
- Potential resource assessment (MWT)
- Environmental and logistical conditions evaluation (accessibility, morphology, protected areas, transmission line distance, etc.)

Step 1
Step 2
Step 3
FINAL OUTPUT

Geothermal Atlas
The Geothermal prefeasibility
Country geothermal scouting – The Preliminary Ranking

- Inferred Temperature
- Inferred size of the area
- Inferred potential (MW)
- Geothermal System Type
- Geological framework
  - Volcano-tectonic setting
  - Natural manifestations (temperature & distribution)
  - Fluid chemistry
  - Hydrothermal alteration
  - Mining exploitation activity

- Defining topic values (numerical or qualitative scale)
- Defining topic weight
- Defining topics combining algorithm
- Algorithm application for each area

Selection of the most interesting areas for further investigations on site

Step 1
Step 2
Step 3
FINAL OUTPUT
The Geothermal prefeasibility
Country geothermal scouting – in field reconnaissance

- Areas selection and in field reconnaissance plan definition
- In field reconnaissance & data collection
- Data evaluation and assessment updating

**Geothermal Atlas Updating**

- Preliminary reconnaissance
  - Natural manifestation census
  - Outcrops and hydrothermal alteration
  - Access roads evaluation
  - Environmental constrains
  - Preliminary geological reconnaissance
- Geochemical survey

- Chemical analysis
- Data elaboration
- Data interpretation (geo-thermometric revised estimation)
- Assessment revision

**Ranking criteria application**

**Final Ranking**

Step 1  Step 2  Step 3  FINAL OUTPUT
The Geothermal feasibility
Main target and phases of the exploration

Ascertain the presence of a geothermal resource and assess the technical-economical feasibility of its exploitation

Two phases

SURFACE EXPLORATION

DEEP EXPLORATION
Mining target delineation and characterization
Index of the main methods applied by Enel Green Power

- Geology and hydrogeology
- Geochemistry
- Geophysics
  - Gravity
  - Magnetotellurics (MT)
  - Reflection Seismic

Surface Exploration tools

Deep Exploration tools
- Well testing and logging

Final goal is the reduction of the mining risk
Geothermal exploration
Typical field implementation of the skills

Exploration skills for well targeting and reservoir modeling can be helpfully used at any stage of the project: **green and brown fields and fields under exploitation**

*Reflecton seismic* would be the most powerful survey for exploration and well targeting but:

- doesn’t work well in volcanic environment
- it is expensive (~10 times the MT)
Surface exploration
Geological and hydrogeological surveys

Surface geological reconstruction
Structural analysis of faults and lineamentes
Studies of mineralization and hydrothermal alteration

Reconstruction of the geological model of the area by field recognition and satellite image analysis
Surface exploration
Geochemistry survey

Collection and analyses of water and gas samples from natural geothermal manifestations (thermal springs, fumaroles, etc.), freshwater and well.

Two main targets:
- identification of areas with geothermal reservoir indicators (H3BO3, CO2, NH3, H2S, etc.).
- estimation of the reservoir temperature and the recharge origin (Isotopic geochemistry).

This activity is particularly useful in the prefeasibility phase.
Surface exploration
Gravity survey

Gravity anomalies, are directly related to the distribution of the density in the earth, therefore can give indications on the structural geology.
MT is a method for determining the resistivity of the earth by analyzing the change in time of the natural electric and magnetic fields.
In volcanic environment hydrothermal fluids circulation at $T < 180^\circ C$, produces argillitic mineralization with low electrical resistivity ($<10$ ohm.m), while circulation at $T > 180^\circ C$ produces propylitic mineralization highly resistive (10-100 ohms. m).

**In the volcanic environment MT may show features directly linked to a geothermal system**
Surface exploration
Reflection seismic - the most powerful investigation method in sedimentary geological environment

Direct indications of the structural geology up to several kilometers with high resolution (order of tens of meters)
Deep exploration
Well logging: tools for the direct characterization of the reservoir

Stratigraphic reconstruction and well correlation
Characterization of fractured layers into the reservoir

Wave form sonic log
Acoustic imaging

Phyllites
Micaschists
Granite

22
Surface exploration
Time evolution of the geothermal targets (Larderello case)

The increasing of the investigation depth and of the drilling cost, requires to apply more powerful and accurate targeting tools.
Correlation fractures/seismic reflections

The H horizon

Encouraging correlation between fractured levels and seismic reflections

These signals are characterized by high amplitudes and correspond to the H seismic horizon inside the metamorphic basement

The H marker constitutes a target for drilling

Seismic method can significantly help in the detection of fractured levels, thus reducing the mining risk
2D seismic dataset: Larderello – Travale area

Integrated interpretation of seismic and well data for the reconstruction of the main geological and structural elements

<table>
<thead>
<tr>
<th>Year of acquisition</th>
<th>Source</th>
<th>Fold</th>
<th>N° of channels</th>
<th>Group interval [m]</th>
<th>Sampling rate [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976</td>
<td>Dynamite</td>
<td>6</td>
<td>48</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>1986</td>
<td>Vibroseis</td>
<td>24</td>
<td>96</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>1987</td>
<td>Vibroseis</td>
<td>30</td>
<td>120</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>1993</td>
<td>Vibroseis</td>
<td>30</td>
<td>120</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>2000</td>
<td>Vibroseis</td>
<td>32</td>
<td>192</td>
<td>30</td>
<td>4</td>
</tr>
</tbody>
</table>

50 seismic lines for a total of about 600 km
3D survey in the Larderello-Travale area

It is difficult to give a target to wells located outside the seismic lines.

2D surveys preclude the possibility to define the true extent of the seismic target.
Recent 3D seismic surveys
Larderello – Travale area

Main acquisition parameters

Source type: dynamite
Bin dimension: 25 x 40 m
Offset range: 0 – 3000 m
Fold: 1600%
Target depth: 3000 – 4000 m

K horizon
Identification of drilling targets
Amplitude analysis of the H marker (Montieri-Chiusdino)

Dataset processed in an “amplitude preserving” way

The amplitude analysis carried out on the H horizon allowed the identification of the target for drilling
Seismic target for the drilling
An example of the result (Montieri-Chiusdino area)
The correspondence between seismic marker and fractured zones was statistically significant.

In the Montieri - Chiusdino area more than 70% of the production comes from the H marker.
The Geothermal feasibility
Evolution of the mining risk (qualitative)

Mining risk can be reduced, but not entirely eliminated
The Geothermal feasibility
Allocation of exploration costs for a geothermal project

- Deep exploration: 10%
- Surface exploration: 2%

A minimum cost for a safer overall investment
Area’s potential in terms of sustainable electrical capacity

Evaluation and definition of all the technical aspects that affect the required Capex & Opex
  • Expected well’s deliverability
  • Well’s depth
  • Interference effects
  • Scaling or corrosion effects
  • Gas content

Designing of the exploitation strategy

Forecast the reservoir evolution (resource availability and/or temperature decline) along the project lifetime

Complex process that requires to define many parameters and to foresee their evolution along the time

Geothermal project’s evaluation process
Target & main elements

<table>
<thead>
<tr>
<th>MWe</th>
<th>Resource assessment (technology &amp; plant size)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>required wells</td>
</tr>
<tr>
<td>MWe/well</td>
<td>M$/well</td>
</tr>
<tr>
<td>Spacing</td>
<td>wells per pad</td>
</tr>
<tr>
<td>$</td>
<td>Opex</td>
</tr>
<tr>
<td>%</td>
<td>Parassitic losses</td>
</tr>
</tbody>
</table>

Prod. & Reinj.: where and how much

Production evolution and make up wells
Once completed the drilling of deep wells it will be issued a final geothermal model that will define size, temperature, productivity and fluid characteristics of the geothermal reservoir.

At the end of the exploration the feasibility of an exploitation project will be quantitatively assessed (Project System).
At the beginning of 20th century... now.....
### Rigs detailed list

<table>
<thead>
<tr>
<th>Type</th>
<th>n°</th>
<th>Max depth (m)</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH 300</td>
<td>1</td>
<td>6000</td>
<td>Advanced Automatic track-mounted RIG</td>
</tr>
<tr>
<td>Mas 6000 E</td>
<td>5</td>
<td>6000</td>
<td>Traditional High Potentiality RIG</td>
</tr>
<tr>
<td>MR 7000 E</td>
<td>1</td>
<td>2000</td>
<td>Traditional Medium Potentiality RIG</td>
</tr>
<tr>
<td>ST6</td>
<td>1</td>
<td>1000</td>
<td>Traditional Low Potentiality RIG</td>
</tr>
</tbody>
</table>

**TOTAL RIGS** 8

3 rig crews operating

365 days/year
Geothermal Drilling
State of art

- High average depth of wells from 3500m to 4500m
- Directional drilling on specific targets with a displacement of over 2000m
- Advanced automatic trailer-mounted rig technology
- Cementing technologies for deep and high temperature wells (350°C) and geothermal oriented tools
- Safety and environmental compliance

- Standard times of drilling activity ~190 days
  - Rig moving ~35 days
  - Drilling ~145 days
  - Well Testing ~10 days
Geothermal Drilling
Main Process

Development
• Mining Proposal
• Investment Authorization
• Budget Approval
• Project Assignment to the Project Manager

• Well Design
• Specific Permitting Processes
• External Resources Planning and Management (materials, contracts and services)
• Quality Systems

• Well pad Lay-Out definition
• Machineries and Equipments O&M
• External Resources Management

• Mining Activity Management
• Drilling Rig Operation
• Management of all other processes supporting the well drilling and completion
• External Resources Management
• Well Testing

Rig Moving

Execution

Well O&M
• Well Operation & Maintenance

DRILLING DEPARTMENT

Mining Development Configuration

• Well Operation & Maintenance
Standard well diagram of a geothermal well
Main data

• Average depth: 4000 m

• Duration of drilling activity: ~190 gg
  » Moving ~35 gg
  » Drilling ~145 gg
  » Tests ~10 gg

• Budget cost: ~6350 k€
  » Moving ~450 k€
  » Drilling ~5900 k€
Standard well
Major components.. about 6000!
Standard well
Moving
Standard well
Drilling data acquisition
Cements and Fluids
Main tasks and skills

- Design of cement jobs in geothermal wells
- Execution of cement jobs, water pumping and stimulation jobs (basic or acid mixtures) (115 jobs per year)
- Maintenance of all the cementing equipment
- Technical management and supervision of all the services related to cementing, stimulation and drilling fluids
- Tuning of the cement slurries in the Cements and Fluids Lab
- Research & Development on drilling fluids
Cements and Fluids
Cement job design

- Design of the job taking considering all the available data and, if necessary, acquisition of missing data

- Definition of the best cementing strategy by means of specific software
Cements and Fluids
Cement job execution

- Placing on site of all the needed equipment and materials
- Set up of the cement
- Execution of the job
Cements and Fluids
Cement job execution

- Dry cement tank
- Service Company cementing Unit to set up the cement
- Batch mixer for the best mixing and homogenization of the cement
- Overfeeding Pump
- Cementing Unit
- Water + Additives tank
- Water
- Cement

Pumping into the wellbore
An entire Geothermal project
Average time-schedule

Geothermal Project Life Cycle
The geothermal resource
The different geothermal system

Depth

0 - 500 m
Dry Shallow Reservoir
Heat pumps – Heat exchange

500 – 5000 m
Hydrothermal Systems: shallow and deep reservoir
Electricity generation - Conventional technologies

More than 5000 m
Hot deep dry rock reservoir
Enhanced geothermal systems - Future perspectives

Exploitation and technologies driven by reservoir characteristics
The geothermal resource
The different geothermal power conversion technologies

Dry steam power plants
Flash steam power plants
Binary cycle power plants

- Dry Steam.
- Water with temperatures higher than ~180°C.
- Water at lower temperatures between ~110-180°C.

Aver. size (MW)
- ~45
- ~35
- ~5
The geothermal resource
The different geothermal power conversion technologies

Installed capacity in MWe for each typology

<table>
<thead>
<tr>
<th>Country</th>
<th>Back Pressure</th>
<th>Binary</th>
<th>Double Flash</th>
<th>Dry Steam</th>
<th>Hybrid</th>
<th>Single Flash</th>
<th>Triple flash</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>48</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>602</td>
</tr>
<tr>
<td>Asia</td>
<td>236</td>
<td>525</td>
<td>484</td>
<td>2514</td>
<td>796</td>
<td></td>
<td>2</td>
<td>3758</td>
</tr>
<tr>
<td>Europe</td>
<td>268</td>
<td>273</td>
<td>795</td>
<td>2133</td>
<td></td>
<td></td>
<td></td>
<td>1642</td>
</tr>
<tr>
<td>Latin America</td>
<td>90</td>
<td>135</td>
<td>510</td>
<td>1642</td>
<td></td>
<td></td>
<td></td>
<td>3450</td>
</tr>
<tr>
<td>North America</td>
<td>873</td>
<td>881</td>
<td>1584</td>
<td>2</td>
<td>60</td>
<td>50</td>
<td></td>
<td>1056</td>
</tr>
<tr>
<td>Oceania</td>
<td>44</td>
<td>266</td>
<td>356</td>
<td>2</td>
<td>259</td>
<td>132</td>
<td></td>
<td>12640</td>
</tr>
</tbody>
</table>

Number of units for each typology (total 613)
The geothermal resource

The different geothermal power conversion technologies

Past 5-10 years

• **Today**
  
  • **Dry steam** (~3 GW of capacity today)
  
  • **Flash steam** (~8.4 GW of capacity today)

• **Binary cycle** (~1.8 GW of capacity today)

Medium term outlook 5-10 years

• **Binary cycle**

Long-term outlook 10+ years

• **EGS** (Pilot project in France)

• **Supercritical Fluid** (Pilot project in Iceland, Italy, Japan)

• **Hybridization; Cascade utilization**

• **Breakthrough**

Conventional

• **Mostly proven** and cost-effective technologies

• **Incremental plant technological advances** going forward

• **Binary only** as an ancillary application due to infancy stage of technological development (i.e., higher costs)

• **Binary** proven to be a self-standing technology, increasing overall installable potential

• **Economics** not yet in line with steam technologies (dry and flash), expected to improve in the long term

• **Technology still in “development” phase**

• **Under certain technological development outlook** (i.e., fast decrease in technology costs), expected to **increase installable potential**

• **Cascade utilization** are already present in the market
The geothermal resource

Reservoir fluid

Steam Dominated

High Enthalpy

Low Enthalpy

Utilization

Electricity Production

Direct uses of the Heat

Water Dominated

Energy Content
Geothermal Electricity: flash and dry steam plant

Geothermal flash power plant
Geothermal Electricity: flash and dry steam plant

Geothermal sheeps – New Zealand

Larderello – Italy
Geothermal Electricity: flash and dry steam plant

Larderello – Italy
Geothermal Electricity: flash and dry steam plant

Berlin – El Salvador
There is a “pot of gold” at the end of the rainbow - USA
Geothermal Electricity: binary plant

Geothermal binary power plant
Geothermal Electricity: binary plant
Geothermal Electricity: binary plant
The Geothermal cost
Effect of well depths, plant size and summary table

MINIMUM UNIT COST based on a 30 MW, medium enthalpy, average values of depth, flow rate and success ratio

<table>
<thead>
<tr>
<th>Cost item</th>
<th>Unit</th>
<th>Magmatic Geothermal Source</th>
<th>Hot Sedimentary Aquifer Geothermal Source</th>
<th>Engineered Geothermal System Geothermal Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wells</td>
<td>$/kW_e</td>
<td>1.250</td>
<td>4,545</td>
<td>7,500</td>
</tr>
<tr>
<td>Steam Above Ground System (SAGS)</td>
<td>$/kW_e</td>
<td>400</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>Power plant</td>
<td>$/kW_e</td>
<td>1,900</td>
<td>2,700</td>
<td>2,400</td>
</tr>
<tr>
<td>Overall Cost</td>
<td>$/kW_e</td>
<td>3,550</td>
<td>7,795</td>
<td>10,450</td>
</tr>
<tr>
<td>Operation and maintenance (variable) power plant</td>
<td>$/kWh</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Operation and maintenance (variable) steam field</td>
<td>$/kWh</td>
<td>0.006</td>
<td>0.006</td>
<td>0.007</td>
</tr>
</tbody>
</table>
The Geothermal cost
Sensitivity studies
Larderello and The Geyser: running capacity comparison
Sustainable Development
Sustainable Development

Natural (reinjected) fluid recharge

Thermal Flux

Exploitation
Sustainable Development

- Wairakei, New Zealand
- Larderello 1 (0,25MW)
- Larderello 2 (6x10MW)
- Larderello 3 (3x24MW+1x26MW)
- Valle Secolo 1-2 (2x60MW)

Deep Exploration 3000-4000 m
Reinjection
Well stimulation

299 Tcal heat supply
3,5 MT CO2 avoided
1,1 Mtep saved
THANKS FOR YOUR KIND ATTENTION!