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Technological Challenges in Risk Management of Carbon Capture and Geological Storage (CCGS) Projects

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Abstract

This article presents the future trend of the Brazilian energy matrix front the immense energy potential of their growing reserves of fossil fuels. This course shift to an energy matrix with more carbon emissions makes necessary the use of mitigation actions among which the Carbon Capture and Geological Storage (CCGS) is the most effective. The paper shows that the risks of CCGS projects are of hybrid origin, a combination of natural and technological hazards, because some of the causes of possible leaks don't depend only on technology operation. This risk management is a technological challenge since there are currently no consolidated technologies commercially available.

Keywords
Carbon capture, geological storage, risk management.

1. Introduction
All human activities that result in combustion generate CO_2 and affect the atmospheric concentration of carbon dioxide. Those anthropogenic influences started to become relevant from the beginning of the industrial revolution and expansions of the agro-pastoralists activities. Among the main human activities that contribute to the growth of CO_2 emissions can be cited:

- Thermoelectric plants that use fuel combustion;
- Extraction wells of fossil fuels;
- Industrial processes that use any form of combustion;
- Any kind of vehicles that use combustion engines and
- Fires for "cleaning" areas for agriculture or for planting of pasture for livestock.

According to the IEA report [1] among the many human activities that produce greenhouse gases (GHG), energy use is by far the largest source of emissions in developed countries. As seen in Figure 1, emissions from production, handling and consumption of all types of energy commodities are responsible for 83% of anthropogenic GHG.
As seen in Fig. 2, the Total Primary Energy Supply (TPES) in the world nearly doubled between 1971 and 2007. The increasing of non-fossil energy participation from 14% to 18% is due to the increasing use of "clean" energy such as hydropower, nuclear power and energy from renewable fuels. However the generation of energy from fossil fuels had an absolute growth of about 5 Gt (Giga tones) of oil equivalent.

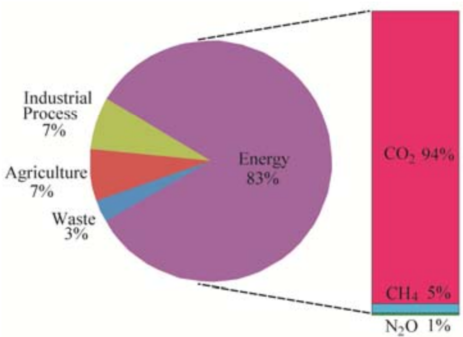

Figure 1: Shares of anthropogenic GHG emissions.

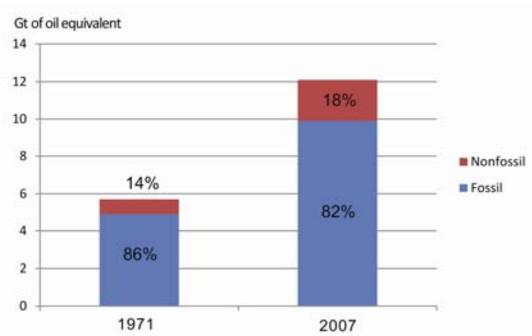

Figure 2: World TEPS.

With increasing demand for energy by the consumer market in emerging countries such as China and Brazil, these countries have as the only short-term alternative the use of fossil fuels. China tends to increase coal use for power generation while Brazil has the medium-term option of using of the huge natural gas reserves yet to be explored.
Use of renewable energy based on biofuels in general, collides with the growing land demand for food production to meet the explosion of world consumption. This explosion is caused by the inclusion of the lowest classes in the consumer market, principally on emerging countries with large populations such as China, India and Brazil.

2. Carbon Capture and Geological Storage – An mitigation step for Climate Change

Carbon Capture and Geological Storage (CCGS) is a process of mitigating climate change by which the CO_2 generated by stationary sources is captured and stored in geological formations.
One might question the importance of using the CCGS since nowadays the petrol engine vehicles are the largest contributors to the increase of greenhouse effect (GHE). However, the vehicles tend to reduce this contribution by the development and gradual shift to other types of engines and fuels. As an example we can mention the electric car. Although the generation of electricity used to power an electric car may come from a "dirty" coal thermoelectric plant, the CO_2 emitted from this plant is concentrated and can be capture. On other hand, capturing CO_2 emitted in a distributed way from these millions of combustion vehicles is economically unfeasible.

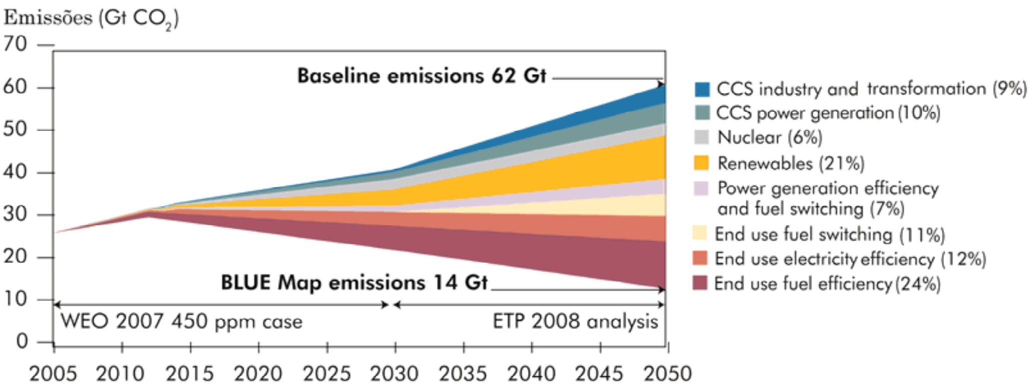

Figure 3: Scenarios for reducing CO2 emissions. Source: IEA (2008)

The IEA (International Energy Agency) study argues that the reduction of GHG emissions can only be achieved by adopting a series of steps and technologies. As seen in Figure 3, tracing lines by the year 2050, the IEA says that if we continue emitting GHG in this indiscriminate way, global emissions could reach 62 $GtCO_2$ (giga tons of CO_2) per year. With a great effort to reduce emissions, by mixing the CCGS, carbon sequestration in biomass, renewable energy, energy efficiency in various ways and nuclear energy, we can reduce overall emissions to 14 $GtCO_2$ per year [2].
The IEA, together with the CSLF (Carbon Sequestration Leadership Forum) prepared the report "Carbon Capture and Storage - Progress and Next Steps" [3] for the G8 Summit in Muskoka, Canada in June 2010. This report lists 80 CCGS projects that satisfy a series of criteria, including the capacity exceeding 500 $MtCO_2$ (mega tons of CO_2) per year and be operational between 2015 and 2020. Nine of these projects are already operational and seventy one are in one of four stages (identification, evaluation, definition or implementation). Seventy three of these projects are located in developed countries, four are in China, two in the Middle-East and one in Africa.
In the graph shown in Figure 4 the report predicts growth for up to 3,400 projects in 2050, of which 65% will be located in countries outside the OECD (Organization for Economic Co-operation and Development). These projects will be responsible for an annual capture of about 10 $GtCO_2$, representing an annual average of 3 $MtCO_2$ per project.

3. Trends of electric power generation matrix in Brazil

The Figure 5 shows the power generation matrix in Brazil according to data from the site of the Brazilian national energy agency (ANEEL) [4]. Brazil has, predominantly, a matrix free of CO_2 emissions, where the hydro generation together with the minimal contributions of nuclear energy and wind power sum 77.1% of all generated electricity in Brazil. Although 22.9% of energy is generated by thermal combustion, predominantly gas plants (45%), however almost a third (31%) of these thermal plants are highly polluting that utilize oil or coal.

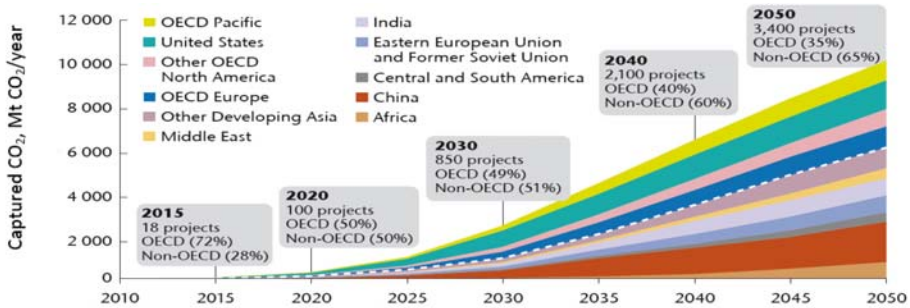

Figura 4 –CCGS Global Development 2010-2050. Source: IEA & CSLF (2010).

The Figure 6 shows the distribution of various types of power generating units under construction according to the site of ANEEL[4]. When comparing the thermal plants in operation (Figure 5) with the ones under construction (Figure 6) is observed an increase of 22.9% to 31%. The coal plants and the biomass plants have increases respectively from 8% to 35% and from 24% to 40%. The oil thermoelectrics have a stable behavior for the same comparison, while the thermal gas plants have a significant decrease from 45% to 4%. This declining participation of gas thermoelectric should be reversed when the vast pre-salt reserves, with a rate of about 200 m^3 of gas per each 1 m^3 of oil, begin to be available.

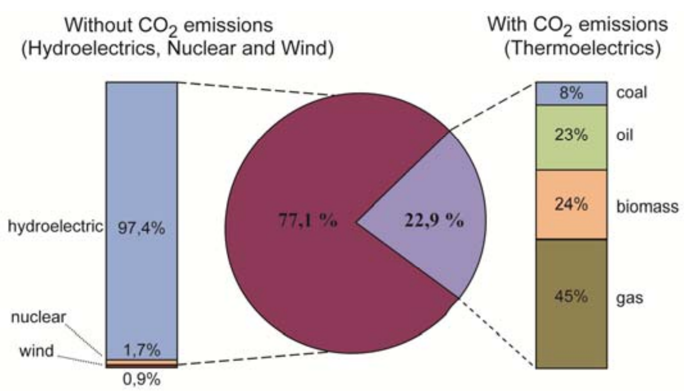

Figure 5: Matrix of power generation in Brazil.

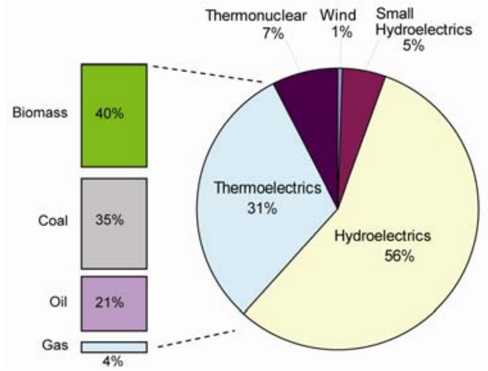

Figure 6: Thermoelectrics under construction.

This growth in the use of thermoelectrics leads Brazil to a matrix with more emissions. Taking data from ANEEL [3] about the participation of the various types of power generation units and taking into account the units in operation (current), the units under construction (short term) and units granted by ANEEL which are not yet in construction phase (medium term) the graphic of Figure 7 is constructed .

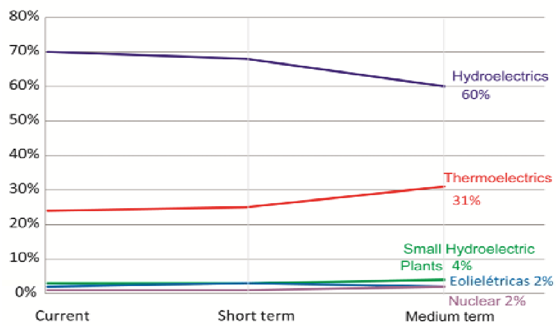

Figure 7: Evolution of Power Generation.

Although a trend towards the medium-term growth of emissions by the system of power generation, this growth is not and will not be a major concern in relation to GHG emissions in Brazil. The focus in the short term is the burnings, which are responsible for most GHG emissions in Brazil. These burnings are the result of agropastoral boundaries expansions that push the savannah biome and amazonic biome. Once resolve the burnings control the priority will be the combating of CO_2 emissions in oil and gas production because it is estimated that the reserves of the pre-salt will produce natural gas with a CO_2 concentration two to three times that of the other reservoirs.

4. Risk Management of CCGS Projects

Risk is the product of the probability of occurring causes and the magnitude of the severity of the consequences. Usually in industrial plants the causes of most of disasters are dealt with management of technology, in other words, specification of equipment and materials, development of standards and procedures, training programs, etc. Thus the search for risk reduction focuses on reducing probability of occurrence of the causes that trigger the series that leads to catastrophic events and their consequences. These consequences are analyzed using data from the surroundings environment, population and natural resources on which it depends. Thus contingency plans and mitigation are proposed if catastrophic events occur.

The risks of CCGS projects are of hybrid origin, a combination of natural and technological hazards, because some of the causes of possible leaks do not depend on technology operation. The reservoir size, demographic changes, the seismic behavior, the micro climate, etc may act by modifying the characteristics of the process and consequently its complexity. Thus we have less control over the causes that may lead to a catastrophic event and it is important to monitor and identify anomalies in the process that can trigger a contingency plan and control de process in advance.

The complexity of risk analysis in the process of CCGS depends on a number of inherent aspects of each project such as separation technology, separation flow, injection flow, distance between the sites of separation and injection, goal of injection, reservoir features, technology of monitoring, substances that form the gas to be injected, etc. The combination of these aspects will determine which risks should have its analysis.

The magnitude and complexity of events involved in the CCGS projects can prevent them from being done with a classic risk management based on administrative procedures and operational controls. Unlike an industrial plant, CCGS process is embedded in a natural body which is responsible for its final function. The performance of the surrounding population and earthquakes can act as the cause and effect in a risks series. Geophysical and geochemical changes in the reservoir, clearly exemplify the odd dynamics of risk management of a project of CCGS, taxing your management system risk adaptive intelligence that can follow this dynamic.

4.1 Risks in Separation, Dehydration and Compression

Due to its punctual characteristic, the risks of these steps are similar to those involved in the industrial process where the CCGS was included. In the case of Weyburn, the coal gasification plant in Beaulah, in the case of Sleipner, the gas production platform. However it should be noted that the addition of units of separation, dehydration and compression of CO_2 increases the complexity of the plant, increasing crossed risks and consequently changing completely the risk analysis.

4.2 Risks in Transportation

Normally the transportation of CO_2 is done by carbon pipelines. The system faults of carbon pipelines may be happen due to two basically causes: a hole or a total rupture. In both cases the fault may be caused by several reasons: corrosion, construction faults, material defects, soil movement, operation error and human activities around the enterprise.

The dispersion of CO_2 behaves in a different way that the gases lighter than air. The scattering occurs in the form of clouds moving near the surface. So the topography and meteorology strongly influence the plume movement.

The most important issue to be analyzed is the CO_2 leakage's impact to human health. The two aspects to be analyzed are concentration and exposure time. The concentration of 150.000 ppm (15% of volume) of CO_2 with less than a minute of exposure time, can lead to the conscious lost. An hour exposure with a concentration between 100.000 ppm and 150.000 ppm can produce a mortality rate between 20% and 90% [5].

4.3 The risk of Leakage of Injected CO_2 for the Atmosphere

The CO_2 is less dense than the saline fluids from reservoirs and thus can migrate to other geological formations underground or to the surface. The escape into the atmosphere can also cause risk to human health and to the environment in the leak vicinity, compromising the effectiveness of GHG emissions control process. The escape of CO_2 at high concentrations can catastrophically affect the local biota.

CO_2 leaks to the surface may occur by pre-existing faults, geological fractures caused by seismic movements induced or not by the storage process, abandoned wells and long-term changes of the rocks of the reservoir.

In an EOR (Enhanced Oil Recovery) process the drilling of new injection wells is done until it is no longer economically viable. Abandoned wells, even if sealed with cement prior to its abandonment, might provide possible routes for CO_2 leakage. This can occur due to degradation of seal materials. The contact of CO_2 with the brine increases by about ten times the attack on the cement sealant compared with pure water [6]. The Weyburn project currently has over one thousand wells across the lateral extent of the migration model. One of the assumptions of studies in Weyburn takes into account an increase of permeability of cement sealing from an initial value of 0.001 md to 1 md during the next 100 years [7].

4.4 Risk of Underground Movements

One of the most important aspects to be analyzed in the underground movement of CO_2 is the ability of carbon dioxide in carry metals. The salt water presence, which occurs in saline aquifers, is important because it promotes the carbonic acid formation, which reacts with the minerals in the reservoir and can transport these metals. The carriage can lead to contamination of potable aquifers nearby .

There are basically two types of rock formation: (1) carbonate rocks (calcite, argonita, dolomite etc.) and (2) siliclastic rocks (quartz, feldspar, etc.).

In the case of silicate rocks the carbonic acid reacts slowly with the rocks and there is little change in porosity and permeability over the injection time. Differently carbonate rocks react faster with CO_2 by changing the porosity and permeability. This effect, however, suffers a damped due to the rapid increase of the pH of salt water leading to a decrease of acid action on the rocks [8].

As an examples of this kind of risk can mention the project developed by In Salah Gas (ISG), a joint venture comprising British Petroleum (33%), Statoil (32%) and Sonatrach (35%). The gas produced by the production wells in the region of the Sahara desert have on average 7% CO_2 and need to have this percentage reduced to a value less than 0.3% to be exported to Europe. To resolve this problem a purification unit was built in the oasis of Krechba [9]. The purified methane heads north on a gas pipeline to interconnect the gas exports network of Algeria, while the captured CO2 is pressurized, transported by carboduto and injected into a saline aquifer located below the gas field. The greatest risk of this enterprise is the possibility of CO2 migration into a fresh water aquifer that is located above the methane reservoir. Investigations showed that the upper part of the reservoir where CO2 is being injected has a thick layer of shale which promotes sealing. However this risk of groundwater contamination should be a priority attention, especially if it is taken into account that this region has a severe shortage of water and a history of violent conflict for water control.

Another risk associated with underground movement is the possibility of seismic shake generation due to geophysics subsoil changes. Moreover the seismic shake can generates a fracture where the injected CO_2 can leak.

4.5 Risks Involved in the Use of Hydrocarbon Reservoirs

Risk analysis in the use of depleted hydrocarbon reservoirs for geologic sequestration or the use of CO2 injection in the process of Enhanced Oil Recovery (EOR) is a complex analysis that should undergo to constant change over time and should take into account the several existing wells in the reservoir. In a reservoir at a given moment, each well will be in one among four possible basic states: (1) production, (2) injection, (3) sealed without instrumentation for monitoring and (4) sealed with instrumentation for monitoring. The state of each of the uncountable existing wells can change at any time. This change brings with it the need of changing the instrumentation required and the ranking of the relevance of the data that feed the risk management.

5. CCGS Policy and Regulation

The deployment of CCGS projects must rely on the approval of the civil society, who must believe that the injected CO_2 will stay stored in the reservoir for thousands of years. To this end, the analysis of possible risks associated with the escape of CO_2 is an essential stage in the life cycle of the storage system and aims to promote and ensure the safety of the activity to the environment and to human health, contributing to technology acceptance.

One major barrier to the onshore carbon sequestration, especially in densely populated areas is the acceptance by the population of the municipalities that are above the reservoirs. Similar fact happens when location study of landfills are done. The citizens of all municipalities want that the garbage generated in their homes and business activities is collected. The entire world population wants the decrease of growth rate of CO_2 concentration . However the acceptance is low for locating a landfill or a geological storage reservoir near its urban or rural properties. The acceptance is low in spite of the ordinary people ignore most of the risks involved in geological storage. In this sense the study of geological storage in saline aquifers or other geologic formations located offshore on the continental shelf seems to be the best option. Broek et al. [10] shows the technical and economic feasibility of constructing a carbon pipeline network linking the power generation units and the industries with intensive emission of CO_2 to the Utsira aquifer, located in the northern sea. This aquifer, which has an estimated capacity of 42 $GtCO_2$ [11] and has been tested since 1996 as a storage option for the CCGS plant of Sleipner. This work took also into consideration the possibility of using the structure to sequester emissions of a part of Germany and Belgium.

6. CCGS Risk Management - a technological challenge

The instrumentation techniques and risk analysis of injection and of tightness of a offshore CCGS process is a technological challenge since, despite the existence of an offshore operative plant in Norway since 1996, the use of reservoirs in deep water requires new monitoring technologies and consequently, new risk management approach.

A literature review brings to the conclusion that the published articles on CCGS risk management just mention the main risks, such as those described in sections 4.1, 4.2, 4.3, 4.4 and 4.5 of this work, without proposing models for creating an integrated system to managing these risks.

The Department of Energy (DOE) of United States in one of their studies [12] only lists the main risks and states that "application of probabilistic risk assessment to geologic CO2 sequestration is still in its infancy".

In his paper of CCGS risk assessment Gerstenberger et al. [13], citing among others: Bowden and Rigg [14], Espie [15] and Kaldi and Gibson [16] states that, "Despite the large body of CCS risk assessment work completed to date we believe that a comprehensive methodology for carbon, capture & storage (CCS) risk assessment does not yet exist and needs to be developed.".

7. Conclusions

The CCGS is a transition choice between the present day, where the global energy matrix is based on fossil fuels, and a future in which global energy matrix will be dominated by carbon-free energy.

Risk management in CCGS is a technological challenge since there are currently no commercially available technologies in CCGS risk management or a conclusive research published on the subject. In addition, the offshore reservoirs to be used for geological sequestration in Brazil have very peculiar features that are very different from others world places.

References

1. IEA (International Energy Agency), 2009, "CO2 Emissions from Fuel Combustion Highlights".
2. IEA (International Energy Agency), 2008, "Energy Technology Perspectives".
3. IEA & CSLF (International Energy Agency & Carbon Sequestration Leadership Forum), 2010, "Carbon Capture and Storage – Progress and Next Steps".
4. ANEEL (Electric Energy National Agency), 2010, "http://www.aneel.gov.br".
5. Koornneef, J., Spruijt, M., Molag, M., Ramirez, A., Turkenburg, W. and Faaij, A., 2010, "Quantitative risk assessment of CO_2 transport by pipelines—A review of uncertainties and their impacts", Journal of Hazardous Materials 177, p. 12-27.
6. Barlet-Goue´dard, V., Rimmele, G., Porcherie, O., Quisel, N. and Desroches, J., 2009, "A solution against well cement degradation under CO2 geological storage environment", Int. J. GHG Control, 3, p. 206–216.
7. Zhou, W., Stenhouse, M.J., Arthur, R., Whittaker, S., Law, D.H.S., Chalaturnyk, R. and Jzrawi, W., 2004, "The IEA Weyburn CO_2 Monitoring and Storage Project – Modelling of the Long-Term Migration of CO2 from Weyburn", Proceedings of the 7th Int. Conf. on GHG Control Technologies (GHGT-7).
8. Wilson, E.J., Friedmann, S.J. and Pollak, M.F., 2007, "Research for deployment: Incorporating risk, regulation, and liability for carbon capture and sequestration", Environ.Sci.Technol. 41, p. 5945–5952.
9. Iding, M. and Ringrose, P., 2009, "Evaluating the impact of fractures on the long-term performance of the In Salah CO2 storate site", Energy Procedia I p. 2021-2028.
10. Broek, M., Ramirez, A.; Groenenberg, H., Neele, F., Viebahn, P., Turkenburg, W. and Faaij, A., 2009, "Feasibility of storing CO_2 in the Utsira formation as part of a long term Dutch CCS strategy. An evaluation based on a GIS/MARKAL toolbox", Int. Journal of GHG Control 4: 351-366.
11. Boe, R., Magnus, C., Osmundsen, P.T. and Rindstad, B.I., 2002, "Geological storage of CO_2 from combustion of fossil fuel", Summary Report of the GESTCO Project, Geological Survey of Norway.
12. Deel, D., Mahajan, K., Mahoney, C.R., Mcilvried, H.G. and Srivastava, R.D, 2007, "Risk Assessment and Management for Long-Term Storage of CO2 in Geologic Formations", United States DOE R&D.
13. Gerstenberger, M., Nicol, A., Stenhouse, M., Berryman, K.., Stirling, M., Webb, T. and Smith, W., 2009, "Modularised logic tree risk assessment method for carbon capture and storage projects", Emergy Procedia 1 (2009) 2495-2502.
14. Bowden, A.R. and Rigg, A., 2004, "Assessing Risk in CO2 Storage Projects". APPEA Journal Australia.
15. Espie, T., 2007, "Risk Assessment for CO_2 Storage in Geological Formations. Moving From Cottage Industry to Industrial Applications", 3rd, IEA Risk Assessment Network Meeting.
16. Kaldi, J.G. and Gibson, C.M., 2008, "Storage Capacity Estimation, Site Selection and Characterisation for CO_2 Storage Projects", Poole (Eds.), Cooperative Research Centre for Greenhouse Gas Technologies: 60.