IS PROCESS ELECTRIFICATION A STRAIGHTFORWARD APPROACH?

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Abstract - Decarbonizing processes is not any more an option. Indeed, it is a challenge for the innovation and transformation capabilities of companies in heavy industries, such as oil and gas. But what is the most efficient manner to achieve it?

Process electrification is reasonably pledged as one of the key solutions, and we assist in the first step, the integration of more and more electricity driven motors than combustion motors. Heaters and boilers are another large consumer of fossil energy, and their accumulated power can range to 10’s or hundreds of MW. But such a massive electrification would have multiple dimensions: sources of energy, hydrogen production, power system design and interconnection among others.

In this paper the authors make a round on the question using project examples from oil and gas and other industries aimed to describe in detail and from a more technical perspective the various challenges for a successful decarbonization.

Would the emergence of low carbon sources as small nuclear reactors, which can supply heat and power, facilitate the transition to decarbonized processes? The authors will give their vision on this subject to invoke a larger discussion.

Index Terms — PCIC energy Paper Format, Writing instructions, Style requirements.

I. INTRODUCTION

In Oil and gas applications the electrification of industrial processes started a time ago. All electric FPSO [1], conversion of gas or steam turbine to electrical drive, [2], [3], are being described during multiple events. However, these actions have been mostly triggered from inside, as a demonstration of willingness to more environmentally friendly production and also as a technical challenge for engineers and operators. In the current context of more politically driven decarbonization, a willingness for energy independence and the development of technologies allowing for higher efficiency, the electrification of industrial processes becomes much more massive in depth and widespread. This rush to the electrical, even in its early phase, can be assimilated to a beginning of an industrial revolution where all players in the heavy industries are assisting and participating. Such a massive electrification will also bring multiple challenges. From an electrical standpoint it will impact two parts of the power system: the sourcing of energy for supplying the loads, through renewable or other alternatives, and the design of the power system where the one-source-feed-all approach may not be the most convenient anymore. In this paper the authors will address these challenges by giving their vision on the evolutions to come and develop it through examples currently seen in upstream and downstream applications.

The paper is structured as follows: the first chapter will explain in more detail the rationale of electrification with examples seen already in industries. The next chapter discusses the main challenges given the scale of change: the loads to be added in the power system and the sources of electrical energy. Locally installed small nuclear reactors as a potential alternative to grid and renewables, or as heating sources are commented in chapter 3. The main design philosophies, brought to the power system when such sources are integrated, are presented in chapter 4.

II. ELECTRIFICATION PROCESS

The electrification at scale impacts the overall value chain in the industrial process, from load to energy source and consecutive power system architecture.

A) Load Side

Industry is the first energy consumer across all sectors with 156 millions terajoules in 2020. Oil & gas industry represents the largest share with one third of it. According to IEA, [4], 78% of this final energy consumption in Industry is non-electrified, lowest electrification rate being in Oil & Gas industry, around 5%.

State of the art for process electrification is presented in following paragraphs, covering various applications that can be categorized into 2 typologies: machine drives and heat.

Machine drives such as compressor, pump.

There is a trend, mainly in China today, to replace all the steam turbines driven by coal boilers with electric motors. The electrical motor conversion will have an impact on the power generation onsite but will provide a higher efficiency and a better CO_2 footprint. The experience shows that even if the electrical generation is coming from coal, an electrically driven system will drastically reduce CO_2 pollution,[5].

2021 data available on worldwide basis for electricity CO_2 footprint is 500kgCO_2/MWh for mixed production (nuclear, renewable, NG, Oil, coal) and 1266kgCO_2/MWh is the average for Air Liquide (China and South Africa) for steam driven Air Separation Unit, ASU, with coal boiler upstream, on our simple steam stream cycle, TABLE I.

TABLE I Air Separation Unit, electrification analyses

	Steam 3000 tpd	Future e-motor 3000 tpd
Elec (MWe / MWm)	- / 44.7	45.5 / 44.7
Steam 80barg (t/h)	167	-
Process water (t/h)	3	-
Cooling Water (t/h)	8877	85
CO2 kg/MWh	**1339**	**400**
CO2 kt/y	**503**	**153**

This transition will obviously require having access to a HV or MV electrical network, which could be an issue as the average individual power of an ASU reaches 42MW. The infrastructure is not always adapted to such industrial applications which require high power and also high short-circuit power to allow the motor, Fig. 1, to start in good conditions.

Fig. 1 Example of large compressor motor

Heat such as furnace, steam boiler, heater, electrolyzer.

The largest share of energy consumption is about generation of heat: In the report [6] it is shown that almost half of the fuel consumed for it in industries can be electrified with technologies available today, from the load standpoint. From low-medium temperature heat, < 400°C for drying, evaporation, distillation, etc.., to high temperature heat, 400-1,000°C i.e. for steam reforming and cracking, electrification does not imply any fundamental change of the related industrial processes. R&D and experimentations are still required for very high temperature heat above 1000°C before scale-up.

Heat in refineries

For an average size refinery (150 thousand barrels/day), heating needs are around 900 MW and are mostly addressed through fossil fuels today. They account for ~63% of the total emissions, exceeding by far the process-related emissions such as fluid catalytic cracking or hydrogen production.

The first loads to target should be steam reboilers and heat exchangers in the range of 1-5MW as they can be electrified with available technologies, Fig. 2:

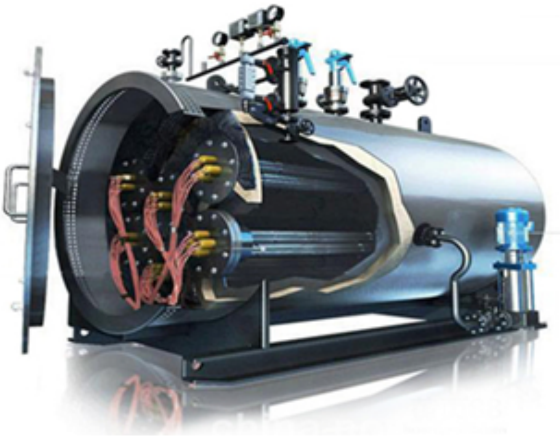

Fig. 2 Example of electric heater concept, courtesy of BALKRISHNA BOILERS PVT. LTD

These initial electrification steps targeting small loads will already significantly impact the electrical power of a standard refinery (50MW), typically with a factor 2. Moving forward, larger fired heaters (over 10MW) and crackers electrification will become possible once the technology will be available at scale.

Production of green hydrogen for the needs of industries to reduce CO_2 footprint

The green hydrogen momentum is pushing the industry to decarbonate their H_2 production by replacing the Steam Methane Reformer (SMR) units with Electrolysis units. For the same quantity of H_2 produced, the gas is replaced by electricity. The systematic replacement of the gas reforming will require a large amount of electricity,

TABLE II:

TABLE II Comparison of Steam Methane Reformer and Electrolyzer technology for 5000Nm^3/h, based on Air Liquide experience

Consumptions	Steam Methane Reforming	Electrolyser
Electrical	150kW	26MW
Gas	2214Nm^2/h	0
Process water	9t/h	5t/h
Cooling water	175m^3/h	0.17m^3/h
CO2 footprint (direct)	4t/h	0

Green hydrogen production also involves conversion from AC to DC, Fig.1, hence it requires careful evaluation of the power system architecture and harmonic mitigation solutions to be compliant with grid code requirements at the lowest cost. One of the mitigation solutions is to use 3 winding transformers in 12 pulse connection on the secondary side,

Fig. 3:

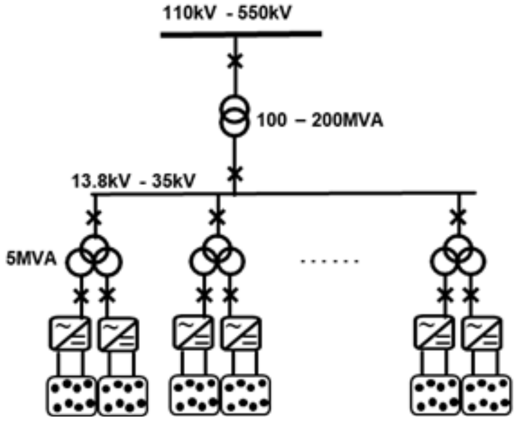

Fig. 3 Example of simplified SLD of hydrogen production

This arrangement reduces the harmonic content on the highest magnitude harmonics 5th and 7th, however it might not be sufficient to be grid compliant.

Glass furnace

Across adjacent industries, glass manufacturing is quite advanced in contemplating natural gas substitution by either electrification of hydrogen. This is driven by a fast-evolving demand from glass industry customers (e.g. beverage / beer industry) on scope 3 CO_2 emission reduction. Important to notice, electrical power in glass melting applications can be almost twice as energy efficient as hydrogen combustion. Experimentations of full electrical furnaces or operation with hybrid furnaces (with electrical boosting), Fig. 4, are underway, part of green glass initiatives.

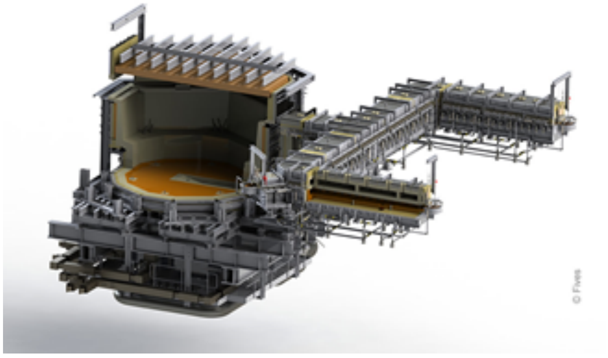

Fig. 4 Example of electrified container glass furnace, courtesy of FIVESGROUP

Electrification of Blast Furnace and DRI (with H_2)

In the steel industry, there are 2 ways of making steel, blast furnace and DRI. Direct Reduction of Iron is the removal of oxygen from iron ore or other iron bearing materials in the solid state, i.e. without melting, as in the blast furnace. The reducing agents are carbon monoxide and hydrogen, coming from reformed natural gas, syngas or coal. Iron ore is used mostly in pellet and/or lumpy form.

Worldwide steel production in 2022: 2 billion tons per year and 100 million tons with DRI process mainly supplied by gas and coal. With the energy transition trend, there is a high interest in using DRI as it reduces the CO_2 footprint by 60% (replacing gas or coal by green H2 produced with electrolysis). As an example, in France the steel industry is producing 25% of the overall industrial greenhouse gas emissions of the country.

Knowing that the production of 2 million tons of steel by DRI will require 1000 MW of electricity (green H2 and arc furnace), the source of electricity will remain a challenge if all steel makers are willing to move in that direction. Arc furnaces are usually worth 200 MWe electric and require stopping every hour, which requires a source of local energy that is powerful and flexible. The level of investment to adapt the electrical infrastructure is huge, counted in billions.

From the above examples it becomes obvious that the process of electrification is moving at different pace in the various industrial sectors, however they all have in common a progressive adoption, following the technology developments, which gives time to the supply and the network infrastructure to adapt.

Most of these electrification applications will require the use of power electronics which will have an impact on the quality (harmonics, flickers, load variations, etc..) of the network on the connection points.

B) Energy supply side

Decarbonization and gas price volatility are one of the major drives for electrification. On the energy supply side, the challenge is translated in various forms depending on the oil and gas process stage:

- In upstream: increase of generation power, onshore connection with sufficient capacity
- In midstream – availability of nearby electrical network
- in downstream: possible connection to grid for substantially higher power, local generation.

As it has been said, for a refinery, where only 5-10% of the actual part of energy is electrical, reaching even 20% of electrification will mean more than doubling of the consumption.

With respect to the necessary quantities of energy and the reliability of the supply, renewable sources installed locally will give only a fraction of the energy. In multiple projects, signing of Power Purchase Agreements (PPA) helps to partially counter this. From a power system architecture standpoint, the addition of renewables or PPA has resulted in little or no changes to the current practices.

Most electrical solution providers tend to push for further electrification and all analysts agree that it is the right path towards decarbonization, [7] . But the challenge is that the electrification of the 24/7 processes requires a huge amount of additional dispatchable power. Newly developed renewables, namely solar and wind are getting relatively inexpensive, but their intermittency does not provide the necessary continuity of service that is a must in manufacturing at present. Their application remains focused on small pieces of process where the existing network can substitute to the renewable energy supply,

Fig. 5:

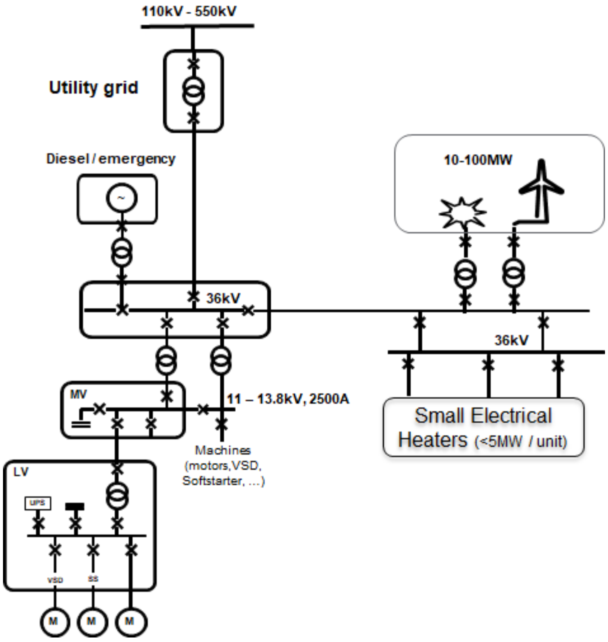

Fig. 5 Example of integration of renewable sources in a plant with small, electrified loads

Although battery storage can help, it is not yet at the scale of the energy, needed in electrified heavy industries, ranging in 10s of MW. At present the vast majority of low-carbon energy supply is performed through green Power Purchase Agreement (PPA) and on-site renewable production, however without guarantee it is produced at the time of the consumption. Industries do not have possibility to buy enough PPA of green baseload at the level of their need, except hydropower or geothermal power in specific sites. Although PPA stimulates the development of renewable energy sources, it also postpones the decarbonization of the baseload power.

In the long term, if all companies follow the same path, it can even trigger a lack of investment in electrical baseload extension and development, generating an energy crisis and consequently, an explosion of energy bills. The more green PPA are contracted, the more intermittent sources are growing on the energy mix, the more the grid is getting unstable, and the more utilities cannot guarantee power availability during winter peaks. This could even lead to the black-out in case of cold-no-wind weather, generating high industry losses and a boom of high CO_2 intensity diesel or coal-based electricity generation. Moreover, with high, >30%, penetration of intermittent sources, the grid stability can be affected, which is critical for heavy industries needing to start large motors and machines.

y the 30’s, in parallel to the process electrification, the lack of dispatchable power will become “The” big bottleneck for industrial projects with high electrical content.

Overall, despite progress in power storage & electronics, electrification of heavy industries will need to continue to rely on stable and controllable power generation. If electrification of processes is to be privileged for decarbonization, it is also important to produce high temperature heat onsite for the processes not suited for electrification.

In [7] can be seen that the general pace of development including developing countries will require huge amounts of metals and other materials, and using renewables is one of the most steel and concrete consuming solutions for electrical energy generation. The metal and concrete footprint of renewable energy sources is to be taken into account with storage. But in the case of electro-intensive facilities that require 24/7 power throughout the year, the storage in the matter of days would require a huge quantity of metallic resources. In a [9], it is estimated that humanity would need more copper overt the next 20 years than during the whole lifetime so far. That is why electrification must be foreseen as a systemic approach, considering the intensity of CO_2, of metallic and concrete footprint that are necessary per unit of KWh produced. As an example, for a 5MW wind turbine, the steel intensity to produce 1 MW is estimated to be 2-6 times more than the same for fossil fuel sources, the copper intensity between 4-13 times higher. With consideration of the intermittent operation of these sources, the above ratios increase, as installed power must be multiplied by 3-5 times to the demand. Consequently, even if in the beginning of electrification such solutions may be sufficient, the massification of electrification will require to evolve on the energy supply side.

III. SMALL MODULAR REACTORS AS ALTERNATIVE SOURCE?

A) Definition

SMR stands for Small Modular Reactors. It encounters very different technologies, being relative to the size of a fission pile that can provide 24/7 energy to the sites. SMRs under development range from 50 MVA to 350 MVA and can generate either heat or electricity. Their footprint/MWe ratio is very low, which allows them to fit in existing sites. They can provide heat from 150°C up to 900°C to industrial processes.

The main difficulty of SMRs deployment is the regulatory changes: in order to be deployed massively into industrial sites at low cost, it is necessary to build giga factories of SMR's, while the manufacturer will be certified once and be authorized to replicate the same model.

B) Very different technologies

Water Pressurized

SMRs will be the first generation available on the market, expected in 2025 [10]. Most of them are under final development around the world, and their core advantage is that they benefit from 70 years of Return of Experience (REX), the level of Technology Readiness Level (TRL) is at 8 to 9. The reactor remains highly pressurized (155 bars) so it requires almost the same rules and safety measures as big classic WPR's. It is safe but it is questionable whether industrial groups with large production sites will consider this technology in its current state, as it is a heavy investment, even though it will provide them energy sovereignty. This technology requires water management onsite, which might not be easily available.

Advanced Modular Reactors

Many start-ups around the world are developing new technologies to achieve the fission easier, faster, closer to the consumers, with less waste, less pressure, at higher temperature and more sustainably. The objective is to provide industries with safety-by-design, so they can be installed anywhere with idiot-proof maintenance, and waste-free design. Ideally it can burn existing waste as-a-fuel to reduce waste inventory duration and volume. There are different types of AMR's under development around the world that already have techno-economic analysis, [11]. Most of them provide new ways to manage safety, and some of them can solve the fuel and waste issue. As an example, fast spectrum-based reactors that can burn most of the waste and can fertilize natural uranium and thorium multiply by over 100 the volume of energy reserves of the world.

C) Which SMR for which application?

Sodium cooled fast reactors

are the only generation 4 reactors that can be fast spectrum, can burn MoX waste, and regenerate its own fuel (by fertilizing natural uranium). The sustainability level is high but it is not proven that the costing will be suitable for a deployment as an SMR in large industrial sites. Due to safety management, sodium has to be fully isolated from water and oxygen, it is likely that the sodium cooled reactors will be in the higher power range (>350MWe) and remain the full property of the utilities at grid level.

Lead cooled fast reactors

are also under development, they are MoX / solid fueled. As for sodium cooled reactors, their peculiarity lies in the temperature management and difficulties to follow fast moving industrial demand.

Triso high Temperature Reactors (HTR)

main advantage is their intrinsic safety. These reactors are usually of high power. The triso pebble used for these reactors can leak. Moreover, the pebbles used as a solid fuel are not recyclable, generating a lot of nuclear waste. Triso pebble reactors have the characteristic to be able to operate at 900°C, which is very interesting for metallurgical processes. It is very likely that the electrical version of triso HTR will remain at grid level, but SMR HTR will be deployed onsite for very high temperature heat applications.

Molten Salt (chlorides or fluorides)

are the most disruptive technology as they operate with a liquid fuel, dissolved into an NaCl classic salt (table salt). The coolant and the fuel are the same. They operate at atmospheric pressure which makes them safe by design, eliminating the risk of heavy radioactive degassing. They are ultra-fast to follow the power demand, which could be very interesting for some industries processes, and well suited for electrical motors in the processes. These reactors may be one of the smallest in size. processes. On Fig. 6 is shown such a reactor placed in the ground, with a very small Nuclear Safety Zone of a few meters, represented with its power train, including heat exchangers, turbines (usually Brayton cycle), and the power distribution (Turbine, turboalternator, and MV power distribution), plus an automation system:

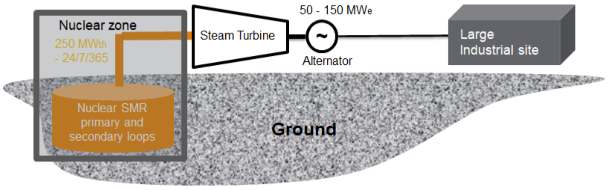

Fig. 6 Schematics of a Molten salt Small Modular Reactor

Additionally, they can also provide heat at over 600°C, which is very suitable for many chemical processes. Providing both from the same reactor is however a challenge.

The molten-salt reactors reach the highest level of sustainability. They are very compact, they can burn nuclear waste, and can even regenerate their own fuel, producing as much fuel as it consumes in core. Their main challenge is that it has a low TRL, so it might take more than a decade to get the first reactors ready to deploy for industrial site. Expectations are that such technologies will be available in the early 2030's.

Comparison of the different technologies is summarized in

TABLE III. It is based on the following criteria:

1/ $\Delta P/\Delta t$: variation of the power generation of the SMR to follow the demand quickly as an average percentage of its nominal power.

2/ Capacity of the fuels to be flexible (use only one type of fuel, or could use many fuels in the sale reactor, and capacity to recycle the fuels of not.

3/ Durability: capacity to reproduce its own fuel during the power production process.

4/ social acceptance: capacity to avoid degassing accident outside of the core by design(low inner pressure) or by procedure (high inner pressure)

5/ Coolant is passive of reactive

6/ possibility to use the reactor just for power, or also in high temperature heat industrial processes.

7/ Technical readiness level.

TABLE III . Comparison of the main SMR technologies based on simple criteria

SMR type	Demand response	Fuel Recyclability	Fuel sustainability	Degazing risk	Fire risk	Multi functions (heat, power, h2)	TRL
Water	Slow (3%/min)	Monofuel, one recycling	U235 only	Limited (300bar)	No	Limited (300°C)	9
Sodium	Very Slow (5% /min)	Monofuel, a few recycling	Regenerate its fuel	No (1.5bar)	Yes	Limited	6
Lead	Very Slow (3%/min)	Monofuel, a few recycling	Regenerate its fuel	No (1.5bar)	No	Limited (450°C)	5
Triso	Slow (3%/min)	Impossible	U235 only	No* (100bar)	No	Yes (800°C)	5
Chloride salts	Very fast (50% /min)	Multifuels, multirecycling	Regenerate its fuel	No (1.5bar)	No	Yes ** (600°C)	3

The SMR technology that will be easily scalable will be the winning technology: high compactness of the source, durability, power autonomy for many years without refueling, regeneration and recyclability of the fuels, flexibility of the power "up and down", easiness to fit in industrial sites, intrinsic safety with no degassing of radioactive gas outside of the nuclear zone by design. Molten salt reactors can fit all the criteria but are still to be developed.

D) *Integration into an industrial site*

The emergence of SMR's will provide a full set of new use cases that will enable decarbonization of heat, power, and molecules, the 3 main elements that are necessary for production in industrial processes.

It can turn the major industrial site into big producers-consumers, helping the electrification of the sites, as well as helping the stabilization of national grids with new decentralized generation.

IV. EXAMPLE OF CONCEPTUAL DESIGN INCLUDING ELECTRIFIED LOADS AND SMR.

A) *Connection options*

Depending on the unit power there could be 2 main scenarios for connection of the additional power, Fig. 7: at the HV level, managed by the utility or inside the plant, which will be mostly the responsibility of the end user.

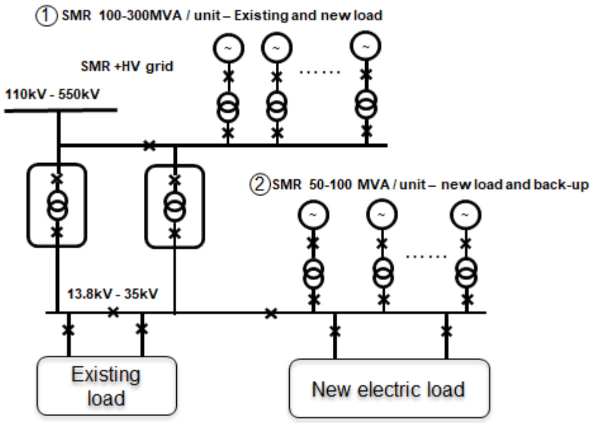

Fig. 7 Connection options for Small modular reactors to an industrial plant

The difference between the two scenarios is mainly in the additional values. For an HV connected source there is possibility to size them to cover the entire need of electrical energy of the plant. In this case the exceeding energy can be injected to the grid and eventually provide ancillary services. The total installed power can reach 0.5-0.8GVA, comparable to some medium nuclear plants. This can be very beneficial if other industrial facilities also do require an increase of electrical energy supply. The drawback would be to modify the protection plan and load flow of the HV network which may have additional cost for the utility. Therefore, this option can be more time consuming to implement.

The second option does not have this drawback, or at least not at the same scale. The connected power is lower, and the step-up transformers do make a barrier to the fault contribution. However, the installed power is limited to the additional loads and potentially some back-up for energy supply, as essential generation. In this case the impact on the protection plan and load flow is on the industrial side but can be managed timely.

B) Progressive inclusion with evolving electrification

As it has been mentioned, the brownfield electrification is a progressive process, which implies that electrical energy consumption marks a step change at every new part getting electrified. In the current very early stage of electrification practice, it can be supposed that the power system evolves in two directions,

Fig. 8:

- adding of new generation close to the load and connected to the existing power system
- creation of isolated power systems individually supplied with local generation, without connection to the existing installation.

The benefit of the first option lies mainly in the possibility to propose additional service of availability of the energy source to the rest of the system, while the other has the advantage to be an independent infrastructure with no impact on the existing installation, which preserves the existing operating modes for the last.

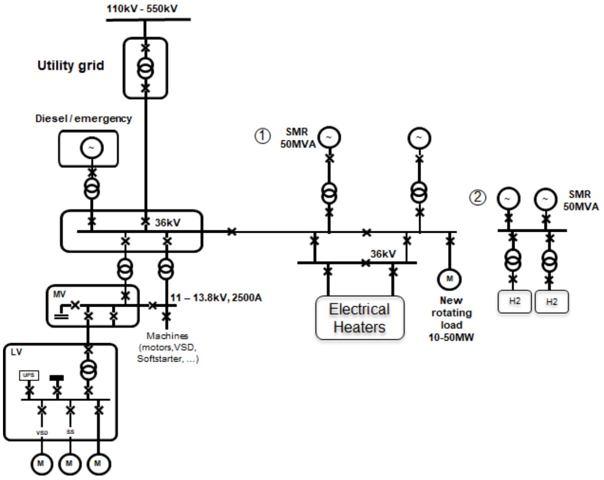

Fig. 8 Example of progressive, on-site inclusion of SMRs, in 2 steps

For brownfield projects, there is one subject to be carefully investigated, related to how the equipment ratings might be impacted if the new generation is integrated in the system. It is difficult to imagine that the whole electrical system will be changed to adapt to short-circuit currents potentially higher. In some situations, the rated currents of connection busbars can also be impacted. Overall, if no change on the existing system is desired, the new energy sources will impose specific operating modes, or the new generators will be designed with impedances such as to maintain the short-circuit current within the limit of the equipment. If generation and connection voltages are different, such current limiting function can be also realized by the transformer. Replacement of equipment can be probably only partial.

C) Impacts on existing power system

Protection Plan

The add of such high-power sources in the industrial installation will modify the fault currents and requirements for protection. The modular reactors drive a synchronous generator, and behavior under fault is same as that of a gas turbine generator. Neutral earthing will be one of the modifications to be considered.

Power quality

The same benefits as with classical generation will exist: no harmonic generation, relatively high immunity to harmonics and capacity to regulate the voltage.

Digitalization

This is where the add of this generators, in particular due to their relatively high unit power and stability will play a role. The possibility of islanded operation, ancillary services or energy bill optimization will turn the multi-objective and multi-criterii control into a key for taking full benefit of this highly reliable and stable capacity of generation.

Safety

The rules for safety in oil and gas plants are already stringent and require a continuous update and improvement through technologies. For some of the small reactor technologies, the safety constraints can turn very close to those already present on site. Overall, this subject will remain an open topic until the technologies come truly live as there are promising safety by design developments.

Maintenance of the reactors

The reactor's maintenance is a subject of agreement, as potentially the servicing will be part of the contract.

V. CONCLUSION

The paper presents a sharing of experience and thoughts of the authors related to process electrification, benefits for CO_2 emissions, and the challenges it will bring not only on the process side but also on the energy supply side. Renewable energy sources are seen as the source of the first step of electrification, while the demand will remain dispersed and relatively low, making possible the back-up from the utility grid. However, in a second step of massive process electrification the energy need will increase tremendously and new source technologies providing high energy density will need to be developed and installed. Such a promising technology is the Small Modular Reactor, using nuclear energy. Main technologies and some possibilities for connection and integration of these sources are discussed.

VI. NOMENCLATURE

SMR	Small Modular Reactor
SMR	Steam Methane Reformer
MTBF	Mean Time Before Failure
MTTR	Mean Time To Repair
SCR	Silicon-Controlled Rectifiers
TRL	
WPR	Water Pressurized Reactor

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VII. VITA

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