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Unitised Regenerative Fuel Cells for Stand-Alone Photovoltaic Generation Systems

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Abstract – Photovoltaic (PV) stand-alone applications are able to provide electricity to isolated loads in remote areas and they are installed particularly where grid extensions would be uneconomical. However, the limitation in power availability of PV systems due to the variability of solar radiation requires the use of storage systems in order to supply loads with adequate reliability levels.
The storage systems have to store a great amount of energy to be maintained for quite long time periods with small losses. This is quite difficult to be achieved by using electrochemical batteries and the use of hydrogen in regenerative fuel cells as a means for energy storage can represent a solution to reach the aforesaid goals.
This paper deals with the use of Unitised Regenerative Fuel Cells (URFC) in the realization of stand-alone PV generation systems. The study of the generation system with solar hydrogen storage will be carried out using analytical models to represent the efficiency of each component in order to assess the capability of the generation system to supply its load with an adequate reliability level in terms of Loss Of Load Probability (LOLP).
In this perspective, a comparison between different storage technologies such as Regenerative Fuel Cells (RFC) and Unitised Regenerative Fuel Cells will be presented. The performance of a storage system based on electrochemical batteries will be taken as reference.

Key-Words – Renewable Energy, Photovoltaics, Hydrogen Storage System, Unitised Regenerative Fuel Cells.

1 Introduction

The installation of stand-alone renewable energy generation systems, such as photovoltaic (PV), at those sites were meteorological conditions are favourable, can bring great benefits in terms of both costs and reliability. In fact, stand-alone applications are able to provide electricity to isolated loads in remote areas and they are installed particularly where grid extensions would be uneconomical. Then, generally speaking, climatic conditions and grid supply availability have a basic influence on the economic evaluation of renewable energy installations with respect to other solutions.

However, the limitation in power availability of photovoltaic systems due to the variability of solar radiation calls for the use of storage systems in order to supply loads with adequate reliability levels. The storage systems have to store a great amount of energy to be maintained for quite long time periods with small losses. This is quite difficult to be achieved by using electrochemical batteries due to low efficiency and self-discharge. At present, the use of hydrogen intended as a means for chemical storage and transfer of solar energy seems to be a solution to overcome the aforesaid limitations [1]. Research in this field proceeds in the development of new technologies to produce hydrogen from water electrolysis. These technologies are, e.g., the Unitised Regenerative Fuel Cells (URFC) [2], [3].

Usually Fuel Cells (FC) are employed for energy generation in Distributed Generation (DG) due to their high efficiency, reliability and environmental compatibility. Further, FC can play the role of energy storage systems. To accomplish this FC need to be coupled with an electrolyser (EZ), which is a hydrogen generator device, to realize the Regenerative Fuel Cell (RFC) system. In practice, the RFC system uses two separate cell stacks: an electrolysis cell stack (EZ) to produce hydrogen and a separate FC stack to generate electric power from stored hydrogen.

The URFC refines this concept by using the cell electrodes to perform both the EZ function and the FC function. Hence, the URFC system uses a single reversible cell stack to alternately produce hydrogen from electrical energy and regenerate electrical energy on demand from stored hydrogen. The URFC systems have lighter weight and smaller physical size than those systems that employ separate cell stack [4].

In this paper, the operation of a PV stand-alone generation system with solar hydrogen storage will be investigated by using analytical models to represent the efficiency of each component in order to assess the capability of the generation system of supplying its load with an adequate reliability level in terms of Loss Of Load Probability (LOLP). Further, a comparison between different storage technologies such as Regenerative Fuel Cells (RFC) and Unitised Regenerative Fuel Cells (URFC) will be carried out by taking as reference the performance of a storage system based on electrochemical batteries.

2 Schemes of a stand-alone PV system with storage

The simplified block diagram of a PV stand-alone generation plant with storage system is shown in Fig. 1.

The storage system based on FC technology is shown in Figg.2 a) and b), respectively, for RFC and URFC. Obviously, the system components of Fig. 1 can not be connected directly to each other for the following reasons:

- different voltage levels in the system;
- control and possible optimisation of global efficiency would be impossible;
- necessity to convert cc waveforms into ac ones.

As a consequence, it is necessary to employ DC/DC and DC/AC converters, with different control schemes according to the various storage technologies, in order to provide power conditioning, efficiency optimisation and subsystems coupling [5], [6]. This work will deal with the plant typologies shown in Fig. 3, where:

- MPPT = Maximum Power Point Tracker;
- DC/AC = inverter;
- DC/DC = converter;
- GC = Gas Compressor.

3 Energy flows assessment

The aim of this Section is to analyse the energy flows within the solar hydrogen system. To do this, analytical models for the various system components in the considered configurations (Fig. 3) have been developed. The basic scheme used for the energy flows assessment is shown in Fig. 4. We define the following quantities:

- λ_i the irradiance on a surface with a given inclination to the horizontal plane during the i-th hour (i=1…24) [kW/m^2];
- P_{Li} = load power demand during i-th hour (i=1…24) [kW];
- A is the array surface area [m^2].

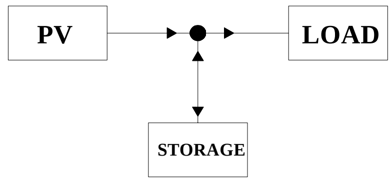

Fig. 1. Simplified block scheme of a PV stand-alone generation plant with storage systems

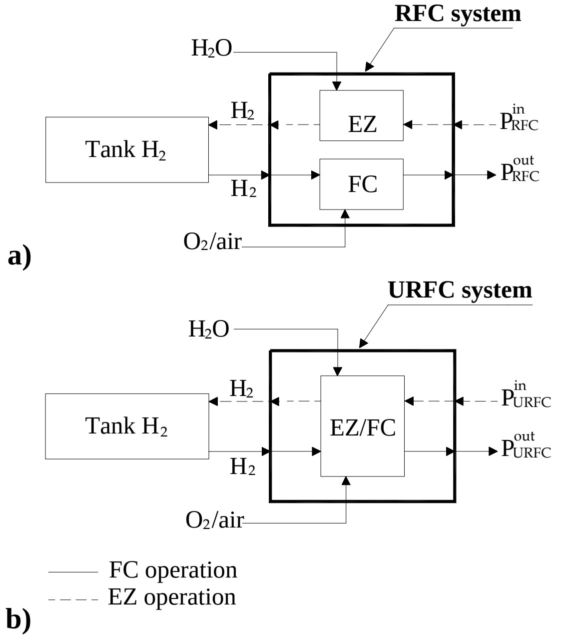

Fig. 2. Schemes for RFC and URFC systems

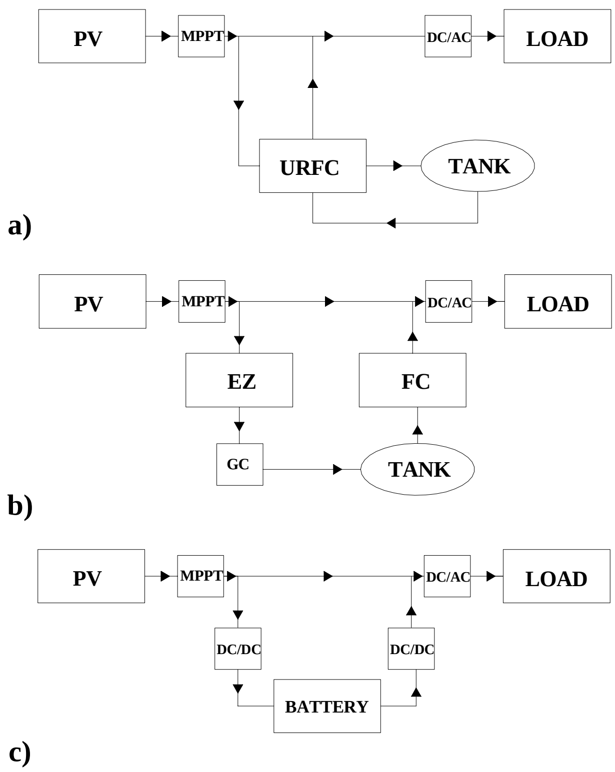

Fig. 3. Configurations with by different storage systems: a) URFC, b) RFC, c) Electrochemical batteries

3.1 Load energy demand

Since load power demand P_L is considered constant during the i-th hour, it can be assumed that $P_{Li}=E_{Li}$ (where E_L is the load energy demand during the considered hour of the year, $i = 1,\dots, 8760$).

The yearly load energy demand, E_{Ly}, is given by:

$$E_{Ly} = \sum_{i=1}^{8760} E_{Li} \qquad (1)$$

3.2 Photovoltaic energy

The energy produced (superscript p) by the PV array during the i-th hour is:

$$E^{p}_{PVi}=A \cdot \eta_{PVi} \cdot \lambda_i \qquad (2)$$

where:

η_{PVi} is the efficiency of the PV array, variable with the hour and solar irradiance λ_i.

The hourly PV energy actually available (superscript a) downstream from the MPPT is given by:

$$E^{a}_{PVi}=\eta_{MPPT} \cdot E^{p}_{PVi} \qquad (3)$$

where η_{MPPT} is the efficiency of the MPPT.

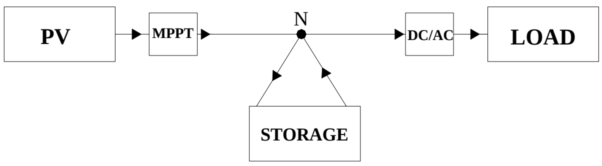

Fig. 4. Basic scheme used for energy flows assessment

3.3 Storage system energy

Two operation modes for the storage system have been identified: the *charge mode* (superscript c) and the *discharge mode* (superscript d).

Accordingly, the hours of the year will be distinguished in "j" hours (*charge hours*), when PV production exceeds load demand, and "k" hours (*discharge hours*), when PV production is lower than load demand. The two operation modes are characterised by different hourly efficiencies, respectively, η^c_{Sj} and η^d_{Sk}.

Charge mode: *definition of "surplus energy" and "stored energy".*

At node N of Fig. 4, during the j-th hour the following inequality holds:

$$E^a_{PVj} > E_{Lj} / \eta_{inv} \qquad (4)$$

where η_{inv} is the DC/AC inverter efficiency.

This means that the PV energy made available exceeds the load energy demand. We have a *surplus* energy, E_{SURj}, given by:

$$E_{SURj} = E^a_{PVj} - E_{Lj} / \eta_{inv} = A\eta_{MPPT}\eta_{PVj}\lambda_j - E_{Lj} / \eta_{inv} \qquad (5)$$

Obviously, a portion of this *surplus* energy can be stored (E_{Sj}). This is due to the storage system efficiency, so that:

$$E_{Sj} = \eta^c_{Sj} E_{SURj} \qquad (6)$$

where η^c_{Sj} is the storage system efficiency in charge mode, variable with E_{SURj}.

The expression of η^c_{Sj} depends on the technology used to realise the storage system:

- URFC $\rightarrow$ $\eta^c_{Sj} = \eta^{EZ}_{URFCj}$
- RFC $\rightarrow$ $\eta^c_{Sj} = \eta^{EZ}_{RFCj} \cdot \eta_{comp}$
- Battery $\rightarrow$ $\eta^c_{Sj} = \eta^c_{BATTj} \cdot \eta_{DC/DC}$

Discharge mode: *definition of "deficit energy" and "provided energy".*

At node N of Fig. 4, during the k-th hour, the following inequality holds:

$$E^a_{PVk} < E_{Lk}/\eta_{inv} \qquad (7)$$

This means that the PV energy made available is lower than load energy demand. We have a *deficit* energy, E_{DEFk}, given by:

$$\begin{aligned} E_{DEFk} &= E_{Lk} / \eta_{inv} - E^a_{PVk} = \\ &= E_{Lk} / \eta_{inv} - A\eta_{MPPT}\eta_{PVk}\lambda_k \end{aligned} \qquad (8)$$

Obviously, the energy actually provide to the storage system, E_{PROVk}, will be greater than the *deficit* energy.

This is due to the storage system efficiency, so that:

$$E_{PROVk} = \frac{E_{DEFCk}}{\eta^d_{Sk}} \qquad (9)$$

where η^d_{Sk} is the storage system efficiency in discharge mode, variable with E_{DEFk}.

Similarly to the previous case, the expression of η^d_{Sk} depends on the technology used to realise the storage system:

- URFC $\rightarrow$ η^{FC}_{URFCk}
- RFC $\rightarrow$ η^{FC}_{RFCk}
- Battery $\rightarrow$ $\eta^d_{BATTk} \cdot \eta_{DC/DC}$

4 Efficiency analytical models of system components

The efficiency analytical models for each component have been derived from experimental data. In the models the efficiency is expressed as a function of the component input / output power:

$$\eta=\eta(P) \qquad (10)$$

As previously highlighted, the hourly input or output power is assumed constant so that, for each given hour energy is numerically equal to power: $P=E$. Consequently, expression (10) is equivalent to the following:

$$\eta=\eta(E) \tag{11}$$

4.1 PV efficiency model

The PV hourly efficiency is expressed as a function of global solar irradiance λ_i:

$$\eta_{PVi} = 9.55\cdot 10^{-2} - \frac{7.9\cdot 10^{-4}}{\lambda_i} \tag{12}$$

The coefficients of the expression have been obtained from experimental measures [7].

4.2 URFC efficiency model

The efficiencies in EZ operation mode (η^{EZ}_{URFCj}) and in FC mode (η^{FC}_{URFCk}) are, respectively, expressed as functions of p^{in}_{URFC} and p^{out}_{URFC}, that are the relative values of input and output power P^{in}_{URFC} and P^{out}_{URFC}, referred to peak powers P^{EZ}_{URFCp} and P^{FC}_{URFCp}, i.e.:

$$p^{in}_{URFC} = P^{in}_{URFC} / P^{EZ}_{URFCp} \tag{13}$$

$$p^{out}_{URFC} = P^{out}_{URFC} / P^{FC}_{URFCp} \tag{14}$$

The obtained efficiency expressions are the following:

$$\begin{aligned}\eta^{EZ}_{URFC} &= 0.89265 - 1.09878\cdot p^{in}_{URFC} + \\ &+ 1.81734\cdot (p^{in}_{URFC})^2 - 1.04471\cdot (p^{in}_{URFC})^3\end{aligned} \tag{15}$$

$$\begin{aligned}\eta^{FC}_{URFC} &= 0.83465 - 0.69088\cdot p^{out}_{URFC} + \\ &+ 0.89368\cdot (p^{out}_{URFC})^2 - 0.64195\cdot (p^{out}_{URFC})^3\end{aligned} \tag{16}$$

The coefficients have been derived from experimental measures carried out on a test URFC of type #9804A (produced by Proton Energy Systems Inc., Connecticut, USA, and tested by LLNL - Lawrence Livermore National Laboratory - California, USA) [8].

4.3 RFC efficiency model

The EZ efficiency (η^{EZ}_{RFCj}) and the FC efficiency (η^{FC}_{RFCk}) are, respectively, expressed as functions of p^{in}_{RFC} and p^{out}_{RFC}, that are the relative values of input and output power P^{in}_{RFC} and P^{out}_{RFC}, referred to peak powers P^{EZ}_{RFCp} and P^{FC}_{RFCp}, i.e.:

$$p^{in}_{RFC} = P^{in}_{RFC} / P^{EZ}_{RFCp} \tag{17}$$

$$p^{out}_{RFC} = P^{out}_{RFC} / P^{FC}_{RFCp} \tag{18}$$

The obtained efficiency expressions are the following:

$$\begin{aligned}\eta^{EZ}_{RFC} &= 0.87289 - 1.38619\cdot (p^{in}_{RFC}) + \\ &+ 2.55711\cdot (p^{in}_{RFC})^2 - 1.41009\cdot (p^{in}_{RFC})^3\end{aligned} \tag{19}$$

$$\begin{aligned}\eta^{FC}_{RFC} &= 0.70721 - 0.74683\cdot (p^{out}_{RFC}) + \\ &+ 1.13758\cdot (p^{out}_{RFC})^2 - 0.77097\cdot (p^{out}_{RFC})^3\end{aligned} \tag{20}$$

The coefficients have been derived from experimental data provided by CNR - ITAE (National Research Council - Institute for advanced energy technologies), in Messina (Italy).

4.4 Battery efficiency model

The efficiency model has been developed on the ground of data provided by [9] and [10].

As said before, it is necessary to take into account a charge efficiency (η^{c}_{BATT}) and a discharge efficiency (η^{d}_{BATT}), respectively, functions of p^{in}_{BATT} and p^{out}_{BATT}, that are the relative values of input and output power P^{in}_{BATT} and P^{out}_{BATT}, referred to peak powers P^{EZ}_{BATTp} and P^{FC}_{BATTp}, i.e.:

$$p^{in}_{BATT} = P^{in}_{BATT} / P^{EZ}_{BATTp} \tag{21}$$

$$p^{out}_{BATT} = P^{out}_{BATT} / P^{FC}_{BATTp} \tag{22}$$

The expressions for battery efficiency obtained are the following:

$$\eta^{c}_{BATT} = \left[1 - 0.2\left(p^{in}_{BATT}\right)^2\right]\left(1-0.1\right)^{(N-1)} \tag{23}$$

$$\eta^{d}_{BATT} = \left[1 - 0.6\left(p^{out}_{BATT}\right)^2\right]\left(1-0.1\right)^{(N-1)} \tag{24}$$

where N=1…10 is the battery year of life that must be taken into account in order to consider the reduction in efficiency due to self-discharge and electrodes degradation. This is important because the battery life-cycle is much shorter than that of FC.

5 Loss of Load Probability

The efficiency analytical models presented in the previous Sections for each component in the various configurations will be employed to assess the capability of the generation system to supply the load with an adequate reliability level.

To do this we will define the known reliability index called LOLP (Loss of Load Probability) as:

$$LOLP = \frac{\sum h_{LL}}{H} \tag{25}$$

where the nominator is the sum of the overall "loss of load hours" (indicated by $\boldsymbol{h_{LL}}$) - discharge hours - during which the storage system is not able to meet the load demand; the denominator, $\boldsymbol{H}$, is the total number of hours in the year (8760).

6 Monte Carlo Simulation

LOLP calculation for the various system configurations has been carried out by means of a software tool developed by the Authors on MATLAB® platform, based on Monte Carlo (MC) method. This method allowed to obtain a realistic assessment of system reliability by using the statistical variations of load demand and PV production. This has been done by means of appropriate statistical models for power demanded by the load and produced by the PV generator [11]. Once the statistical models are defined in terms of probability density functions (pdfs) the procedure involves repeating the simulation using each time (hour by hour) a particular value of the random variables (load demand and PV production), generated according to the corresponding pdfs.

For each hourly simulation it is possible to assess whether the considered hour is a "loss of load hour" or not. The simulations are then extended to the overall year, thus obtaining the sum of the loss of load hours and then the value of the LOLP for that year ($LOLP_y$).

To ensure a reasonable accuracy of the calculation performed by the Monte Carlo method, an appropriate number of years (Y) is to be considered. The final result will be the average LOLP value:

$$LOLP = \frac{\sum_{y=1}^{Y} LOLP_y}{Y} \tag{26}$$

7 Numerical results

This section presents the results of the analysis carried out to assess the reliability in terms of LOLP index for the three configurations characterized by different storage systems. In particular the values of $LOLP_{URFC}$, $LOLP_{RFC}$ $LOLP_{BATT}$ will be reported in the graphs of Figg. 6, 7, 8 and 9 as a function of p (adimensional) which is defined as the relative value of P_{Pvpeak} (kW) referred to the daily average value of load demand, P_{Lav} (kW):

$$p = \frac{P_{PV\,peak}}{P_{L\,av}} \tag{27}$$

where P_{Pvpeak} is the value of power generated by the PV system in standard conditions (Solar Irradiation=1kW/m^2 and Cell Temperature=25ºC).

The aforesaid graphs are characterised by different capacities, E_s (kWh), of the storage system expressed in terms of "equivalent hours" (h_e), defined as:

$$h_e = \frac{E_S}{P_{L\,av}} \tag{28}$$

In physical terms, the quantity h_e represents the number of hours during which the storage system is able to meet a load demand equal to P_{Lav}.

The results obtained are referred to an ideal load diagram (shown in Fig. 5) which brings about the maximum energy storage.

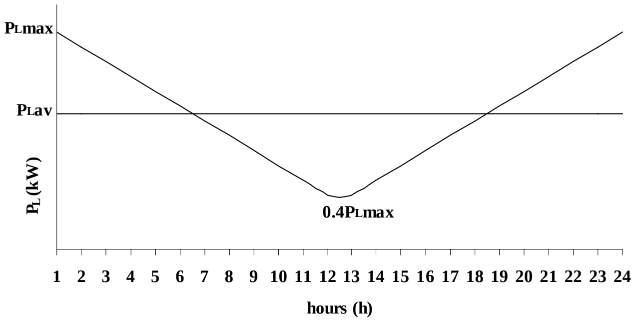

Fig. 5. Ideal daily load diagram

This is because the concern is on the operating condition in which the storage system assumes the most critical role from the reliability viewpoint. This condition is when the generation diagram has its maximum during minimum load hours. Hence the surplus energy is maximum with respect to load demand.

Graphs of Figg. 6, 7, 8 and 9 show that the PV generation system with hydrogen-based storage technology is more reliable than the system with electrochemical batteries. Further, the configuration with URFC has a lower LOLP (reduced by a 10%) than the configuration with RFC. Consequently, the URFC, besides being advantageous in terms of light weight and small physical size, ensures higher reliability levels than those systems that employ separate cell stacks (RFC).

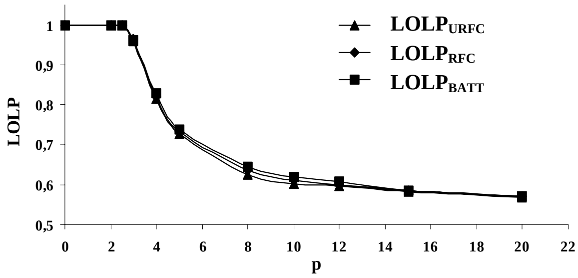

Fig. 6. LOLP graphics with h_e=1

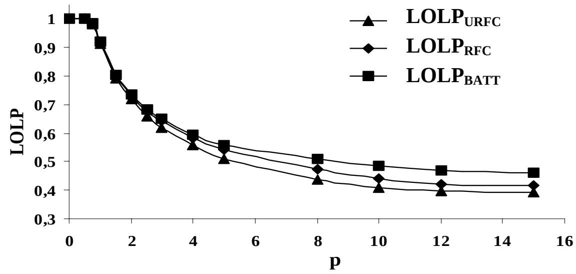

Fig. 7. LOLP graphics with h_e=12

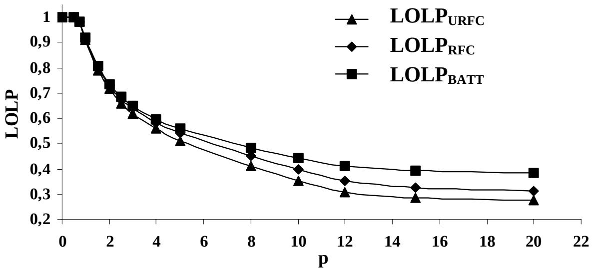

Fig. 8. LOLP graphics with h_e=24

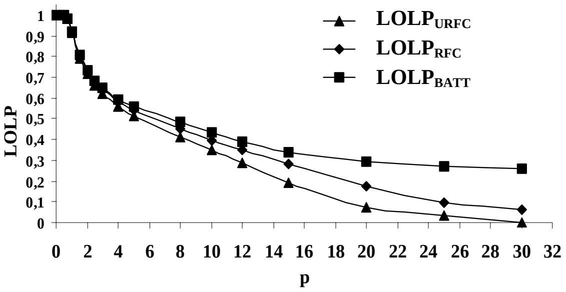

Fig. 9. LOLP graphics with h_e=48

4 Conclusion

In this paper, the operation of a PV stand-alone generation system with solar hydrogen storage has been investigated by using analytical models to represent the efficiency of each component in order to assess the capability of the generation system to supply the load with an adequate reliability level.

This allowed a comparison between different storage technologies such as Regenerative Fuel Cells (RFC) and Unitised Regenerative Fuel Cells (URFC), carried out by taking as reference the performance of a storage system based on electrochemical batteries.

The aforesaid comparison resulted in the higher reliability level of the PV stand-alone generation system with hydrogen storage as referred to the use of electrochemical batteries. Further, as for the hydrogen storage system, the URFC guarantees higher reliability level than those systems that employ separate cell stacks (RFC).

This makes the URFC technology very attractive to store energy in the form of hydrogen and to produce electrical energy from the stored hydrogen as well.

However, URFC technology still involves uncompetitive costs as compared to RFC technology (URFCs are only employed in space applications where the high costs are determined also by the use of precious materials).

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