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A procedure for evaluating microgrids technical and economic feasibility issues

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Abstract **– Microgrids exploitation is one of the most useful and efficient ways of integrating Distribution Generation (DG) technologies. Microgrids allow to realize a coordinate control of different DG facilities, and to provide proper control strategies to the distribution grid. In this paper, economical involvements affecting decisions of realization of microgrids are assessed. Furthermore, a procedure for economical evaluation of microgrids is proposed, aiming to minimize costs in the presence of different constraints. The procedure is applied to a test system representing a cluster of residential final users and services, and various cases are analyzed, in order to account for different choices for energy supply.**

Index Terms **– Distributed Generation, Microgrids, Economic Analysis**

I. NOMENCLATURE

Indices:

y = year of the time horizon;

d = day of the year;

h = hour of the day;

t = technologies for electric energy supply:

- *PV* (photovoltaic);
- *WT* (wind turbines);
- *GmT* (gas micro-turbines);
- *g_IN* (power coming from the grid);
- *g_OUT* (power flowing towards the grid).

Cost Voices:

$oc_{y,t}$ operation cost of t-th technology at y-th year (€/kW);

$ic_{y,t}$ installation cost of t-th technology at y-th year (€/kW);

$fc_{y,d,h}$ fuel cost for electricity generation during the h-th hour of the d-th day at y-th year (€/kWh);

$ec_{y,d,h}$ cost for electric energy withdrawal from the grid during the h-th hour of the d-th day at y-th year (€/kWh);

$gc_{y,d,h}$ cost for electric energy injection to the grid during the h-th hour of the d-th day at y-th year (€/kWh);

cc_{y} cost for microgrid control systems y-th year (€/kW);

$inc_{y,d,h,t}$ incentive relevant to energy production from t-th technology during the h-th hour of the d-th day at y-th year (€/kWh).

State Variables:

$IP_{y,t}$ installed power of t-th technology during the y-th year (kW);

$P_{y,d,h,t}$ energy production from t-th technology during the h-th hour of the d-th day at y-th year (kWh).

II. INTRODUCTION

The conventional approach to distribution system planning included centralized electricity production and distributed energy use, being the two sides connected by means of passive distribution networks used for energy delivery. The penetration of Distributed Generation (DG) has emerged as a promising option to meet growing customer needs for electric power with an emphasis on reliability and power quality [1]. As DG spreading is not centrally planned, the integration in the main distribution grid of a remarkable amount of DG facilities can cause technical problems associated with protection and control systems [2]. Therefore, new models for energy delivery need to be studied. Distribution grids are required to change from passive to active network, so that control is distributed and power can flow bidirectionally [3]. In this sense, distribution networks are moving towards the concept of “Smart Grids”, using real-time communication and remote control to meet network services requirement, with harmonised and real-time interacting control functions and efficient power flow [4].

The realization of active distribution networks will include the implementation of new concepts, and considering generation and associated loads as a subsystem or a “microgrid” [1][5] is one of these. Microgrids are systems that include DG devices, storage systems and associated loads, with a total installed capacity in the range of a few hundred kilowatts to some megawatts. Although microgrids operate mostly connected to the distribution network, they can be

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transferred to islanded mode, in case of faults in the upstream network and can be reconnected after restoration [4].

In traditional energy use, little attention is paid on energy balance, but the installation of a microgrid, having a remarkable contribution from intermittent energy sources, basically renewables, involves a deep investigation of this item, in order to evaluate the need for storage systems [6].

Besides connection regulation and development of technical standards, various Countries have designed policies to foster DG penetration, such as financial incentives in investments, exemption of transmission charges, obligation policies and energy production reward [2]. These choices attempt to moderate commercial, technical and security barriers to DG spreading [7].

In Italy, these policies have found expression in special incentives on energy production from photovoltaic systems [8], in conditions for net metering for micro-generation facilities below 20 kW [9] and in choices for reserved electric energy delivery for DG plants under 10 MVA and for all renewables at facilitated price levels [10].

A microgrid may bring benefits such as the reduction of energy costs, the improvement of reliability of the electric network, the deferral of investments in distribution network capacity, and the reduction of network losses. Social benefits can come by lower exposition to grid faults and lower environmental impact [11].

Feasibility of microgrids is affected both by technical and economic issues. Technical issues include connection schemes and control strategies within the microgrid, even in islanding conditions. On the other hand, economic evaluation greatly affects practical implementation of microgrids [12]. In fact, cost-efficiency of investments in DG requires a careful analysis, taking into account: incentive policies, saved costs due to avoided energy purchasing, rewards for energy sold to the grid.

Various studies have been carried out on the investigation of economic involvements of microgrids exploitation at different levels. For instance, [13] presents a methodology for the evaluation of economic operation of a microgrid focusing on operation issues of multiple facilities based on Combined Heat and Power (CHP) generation, such as space heating, absorption refrigerators, hot water. Furthermore, [12] illustrates a methodology for evaluating construction and operation costs of microgrids, including power interruption issues and storage systems, and evaluating the involvements of the realization of different integration levels of supply and loads. On the other hand, the work [14] is focused on economic effects of reliability improvement coming from microgrids, whereas [15] provides an optimization methodology for the design of DG plants in the presence of different contracts for energy withdrawal and delivery.

In this paper, an optimization procedure for the evaluation of technical and economic feasibility issues of a microgrid is proposed. This procedure aims to minimize investment and operation costs related to various microgrid configurations. Different DG technologies are taken into account, exploiting renewable sources and microturbines. Simulations are carried out on a realistic system acting under the Italian regulation of electricity and gas supply and of support for local power generation.

III. Methodology

In the presence of deregulated energy markets, microgrid investors need to evaluate the convenience of generating power locally. To this purpose, an optimization-constrained procedure, able to minimize economic efforts, is adopted. It can be synthesized as follows:

$$\begin{aligned} &\min \mathbf{f}(\mathbf{x}) \\ &\text{s.t. } \mathbf{A_e} \cdot \mathbf{x} = \mathbf{b_e} \\ &\mathbf{A_i} \cdot \mathbf{x} \le \mathbf{b_i} \end{aligned} \qquad (1)$$

The objective function $\mathbf{f(x)}$ is minimized over a definite time horizon with respect to state variables included in vector $\mathbf{x}$. The time horizon is divided in periods, corresponding to years, and each period is further splitted into sub-periods, representing hours of the day. State variables include new power installations of DG solutions in each period and electric power flows during each sub-period into which the selected time horizon is divided. Function $\mathbf{f(x)}$ represents the total cost of the microgrid, and it is composed by three terms: investment cost $\mathbf{IC(x)}$, operation costs $\mathbf{OC(x)}$ and revenues $\mathbf{RE(x)}$, as reported below:

$$\mathbf{f(x)} = \mathbf{IC(x)} + \mathbf{OC(x)} - \mathbf{RE(x)} \qquad (2)$$

Investment costs mainly include costs for the procurement of new power generation devices and microgrid control equipment, evaluated on a year basis, and can be expressed as in the following formula:

$$\mathbf{IC(x)} = \sum_{y}\sum_{t} ic_{y,t} \cdot IP_{y,t} + \sum_{y} cc_{y,t} \sum_{t} IP_{y,t} \qquad (3)$$

Operation costs include maintenance costs and expenses for purchasing energy sources. Purchasable energy sources can be fuels, for instance natural gas, or electric energy. In the latter case, this cost is related to the amount of electricity withdrawn from the main grid in order to satisfy the demand. The overall expression including these three terms is reported as follows:

$$\begin{aligned} \mathbf{OC(x)} = &\sum_{y}\sum_{t} oc_{y,t} \cdot IP_{y,t} + \\ &+ \sum_{y}\sum_{d}\sum_{h} fc_{y,d,h} \cdot P_{y,d,h,GmT} + \\ &+ \sum_{y}\sum_{d}\sum_{h} ec_{y,d,h} \cdot P_{y,d,h,g\_IN} \end{aligned} \qquad (4)$$

Revenues from microgrid activity can come from incentives to energy production and from energy sold to the grid. In fact, as renewable-based technologies such as photovoltaic and wind turbines, can be exploited within microgrids, suitable sustaining policies can be adopted in order to allow a wider spreading of DG. Moreover, if the energy generation exceeds load needs, it would be possible to sell the remaining power to the grid, achieving a further gain. Energy flows from local generation technologies and power grid are estimated on hourly basis. This leads to the following expression:

$$\begin{aligned}\mathbf{RE(x)} = \sum_{y}\sum_{d}\sum_{h} gc_{y,d,h} \cdot P_{y,d,h,g\_OUT} + \\ + \sum_{y}\sum_{d}\sum_{h}\sum_{t=\mathrm{PV,WT}} inc_{y,d,h,t} \cdot P_{y,d,h,t}\end{aligned} \tag{5}$$

Equality constraints $\mathbf{A_e} \cdot \mathbf{x} = \mathbf{b_e}$ deal with electric energy balance: in each sub-period (hour), load demand has to be equal to total generation from DG facilities and net power coming from the grid. In this formulation, electric loads are supposed to be an input to the problem, in the form of suitable duration curves.

Inequality constraints $\mathbf{A_i} \cdot \mathbf{x} \le \mathbf{b_i}$ involve different aspects of microgrid operation:

- global power installation of each generation technology is bounded by a value coming out by investigations on available sources and areas;
- power exchanges with the main network have to be limited to the contractual value;
- energy generation from renewable sources, such as wind and solar radiation, is bounded by the availability of these sources, supposed that useful data can be known in advance of at least one day as average values.

The analysis is performed in an hourly perspective, aiming to evaluate the behaviour of each energy generation device during a daily operation scheme, and it encompasses an eight-year time horizon.

IV. Test System

The proposed procedure is applied to a realistic energy system, representing a residential city district, whose data are taken from [16]. The case system includes:

- a school building, covering an area of 4,700 m^2, with a global installed power of 600 kW and average equivalent duration of 3,000 h/year;

- a building complex including offices and public services, exploiting an area of 27,000 m^2, having a global installed power of 2,934 kW and average equivalent duration of 3,500 h/year;

- a supermarket, covering an area of 3,500 m^2, with a global installed power of 1,637 kW and average equivalent duration of 5,500 h/year, due to the presence of cooling systems for air conditioning and for refrigerators;

- a residential complex, composed of 600 dwelling units, with a global surface of 30,000 m^2, having global installed power of roughly 500 kW and average equivalent duration of 5,000 h/year.

The global area is of roughly 65,000 m^2, and the total nominal electric power of the loads is of 5,600 kW. Within this area, three DG technologies are considered suitable for installation: mini-wind turbines (WT), photovoltaic (PV) panels properly oriented, and gas-fuelled micro-turbines (GmT), exploitable thanks to the presence of a gas distribution network. The maximum power installations for each generation technology (i.e. number of PV panels, of WT, of GmT) depend on the available area and on unit power. A preliminary investigation of these issues has been carried out, and relevant results are listed in Table 1, together with the value of power for contract of supply and exchange of energy with the distribution system operator, limiting power flowing through the interconnection.

TABLE I
LIMIT OF POWER INSTALLATIONS [k€]

Facility	Unitary installation	Maximum number of units	Total Power [kW]
Photovoltaic (PV)	120.5 W/m^2	8,300 m^2	1,000
Wind turbines	20 kW	75	1,500
Gas micro-turbines (GmT)	100 kW	30	3,000
Installed power for withdrawal	---	---	5,600
Installed power for injection	---	---	4,500

Hourly load curves are evaluated considering six typical days. In particular, in whole year three seasons are individuated, winter, summer and between-seasons, and two kind of days are working days and holydays. This distinction reflects the differences in load duration curves actually present in industrialized Countries, and it also allows a simple and general evaluation of problem solution, as global operation costs are obtained by just multiplying costs for a typical day by the number of this kind of day in the year, as proposed by [12] and [13]. Examples of load duration curves for summer working day and between-season holyday in the first year are reported in Fig. 1. These typical days are characterized by the maximum peak load and the minimum off-peak load respectively. It can be noted that differences in energy needs between these two typical days are remarkable for offices, school and supermarket, whereas changes in consumption of residential users are comparably negligible.

The end-user demand is supposed to grow yearly by a 2% rate for all kind of customers [16].

The distinction of typical days is useful also in order to evaluate the energy potential of renewable sources, such as wind and solar radiation, whose data are taken from [17]. According to the placement of the system under study, located in Apulia region in southern Italy, suitable hourly curves for availability of primary sources are accounted, and available power is obtained by matching these curves with properties of the technology under investigation (for instance, power generation at a certain hour of a given day from wind turbines is obtained by matching average wind speed in that hour with suitable power curve of wind turbine).

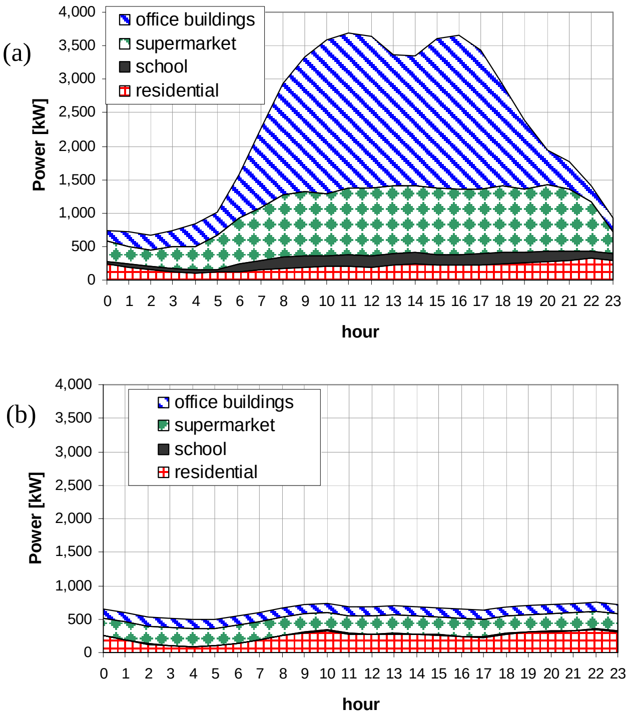

Fig. 1. Load duration curves for summer working day (a) and between-season holyday (b) at the reference year.

V. CASE STUDY, RESULTS AND COMMENTS

The proposed procedure is applied to three cases:

- Case A: no microgrid is present, and electricity demand is covered by contracts with distributors;

- Case B: the installation of DG facilities within the microgrid is allowed, and demands for natural gas and further electric energy are satisfied by means of contracts with distributors.

- Case C: the microgrid manager decides to play in the electricity market, buying the needed extra quantity of energy and selling the amount exceeding the demand in the market itself. Moreover, supply for gas consumption is also taken from the market[1].

For the assessment of Cases A and B, tariff values for electric energy and gas are taken from [18]: for 2008, average values are 28,75 c€/kWh for electric energy distribution and 67,26 c€/m^3 for natural gas contracts. Suitable linear variation trends are imposed, according to tariff variations over the last five years. Moreover, for Cases B and C, incentives for PV installations are evaluated according to Italian legislation prescriptions [8], amounting to 36 c€/kWh, as it is supposed that PV generation systems are not architectonically integrated in buildings. Whereas, incentives to wind production are in the form of green certificates, as Italian legislation provides, and their base value is 13,7 c€/kWh [19], and suitable increasing trends are evaluated according to values of green certificates in the last four years.

[1] This scenario has become possible thanks to deregulation in Italian energy market, allowing all final users to select the kind of supply they prefer in order to gather energy sources.

Furthermore, in order to develop case C, average electricity price data in the market are derived from Italian Market Operator [19] and amount to 8,24 c€/kWh for the base year, whereas prices for natural gas supply from free market are taken from Italian Authority for Electric Energy and Gas [18] and are estimated at 29,82 c€/m^3. For these two items, suitable logarithmic trends are estimated for the following years on the basis of experienced values in these fields in Italy.

Investigation on Case A shows that, since no DG installations are provided, the whole load is satisfied by power coming from the grid, and the hourly load curve correspond to power withdrawal from the distribution grid. This represents the reference case for comparison with other two cases.

In Case B, PV and WT are fully exploited from the first year, amounting to 1 MW and 1.5 MW respectively and 2.1 MW of GmT are installed during the first year. Hourly diagrams concerning the last year results are reported in Fig. 2, representing summer working day (a) and between-season holyday (b).

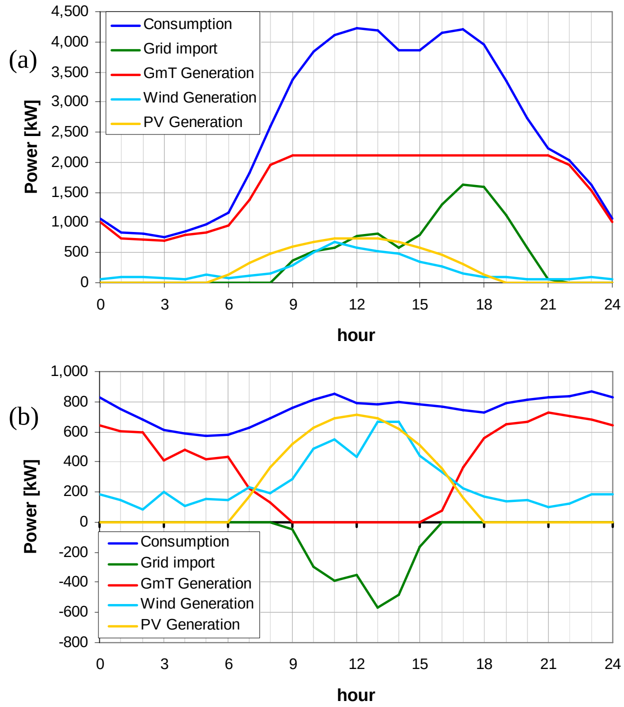

Fig. 2. Case B. Hourly diagrams for summer working day (a) and between-season holyday (b) at the eighth year.

It is clear that energy coming from DG facilities is not always able to cover the whole demand, and some contribution from the grid is desirable. Hence, GmT are required to cover most part of the load, meaning that purchasing gas and burning it to locally generate energy turns out to be preferable and more convenient than purchasing power from the grid. Renewable sources are fully exploited, according to their availability.

Moreover, from Fig. 2.b it can be seen that, between hours 8 and 16 of holydays, power is exported to the distribution network, as load demand is lower than production. GmT production reduces to zero during the same time interval. This is ascribable to the fact that generating power by means of GmT, even convenient in order to satisfy local demand, is not economically favourable for energy selling to distribution grid. In fact, no incentive is related to this kind of generation, and the only revenue comes from selling energy at a reserved price, lower than cost for purchasing electric energy from distributors.

In Case C, PV and WT are exploited as in Case B, i.e. to 1 MW and 1.5 MW respectively, fully installed in the first year, whereas GmT are not considered at all. This is due to lower price for electricity supply, as microgrid purchases directly from market at market price, and this generates a lower convenience for natural gas exploitation, as difference between distribution cost and market cost for natural gas is slight.

Hourly diagrams for last year are illustrated in Fig. 3, corresponding to those reported for Case B in Fig. 2. In this case, the role of supplying power when intermittent sources, usually fully exploited, are not available is assigned to power withdrawal from the distribution grid. As in Case B, power is exported during holydays, when renewable generation exceeds load demand.

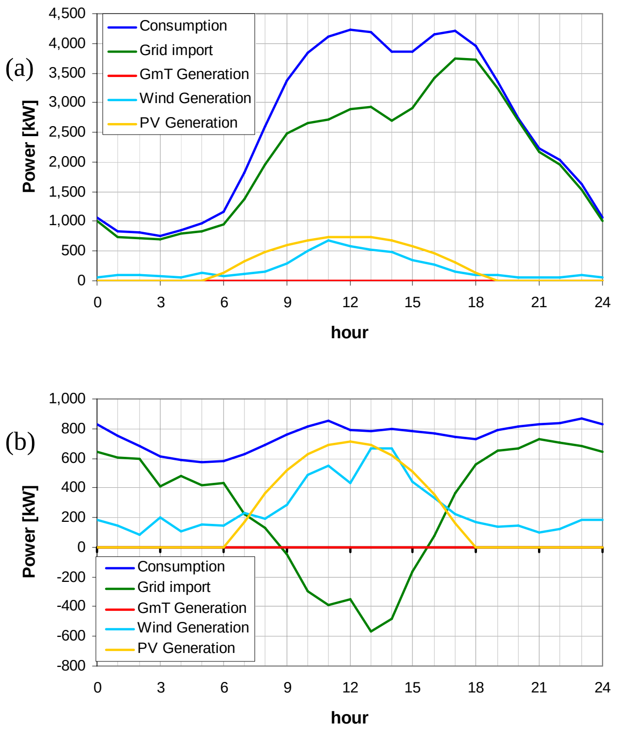

Fig. 3. Case C. Hourly diagrams for summer working day (a) and between-season holyday (b) at the eighth year.

An outline of actualized costs over the planning horizon is reported in Table II, where cost components are divided per technology. It has to be remarked that revenues for renewable-based generation facilities are related to incentives for energy production, whereas revenues reported under the "Grid" column concern the energy sold. Furthermore, installation costs in "Grid" column are relevant to devices devoted to microgrid management and control, such as smart metering devices, communication lines, control processors, local sensors, that can contribute to improve power quality indices of the microgrid. Cost of control devices is taken into account according to data from [12].

Overall cost for supplying loads without any DG facility, as in the Case A, amounts to 40,594 k€ over the whole horizon, and it is related to electric energy withdrawal from the distribution grid.

For the Cases B and C, installation costs for renewable options are recovered by means of related incentives on energy production. This yields to a total cost, calculated as from eq. (2), that is negative for wind installation and close to zero for PV plants, indicating that strong incentives really foster production from renewables. Moreover, in Case B, energy conversion from GmT resulted less costly than purchasing energy from the grid, pushing for the installation and exploitation of microturbines. The realization of the microgrid yields a saving of roughly 30% of expenses compared to a traditional passive connection..

Results of Case C show that the choice of turning to energy market instead that distributors in order to provide for electric energy and natural gas reveals a powerful solution for cost reduction. In fact, total cost falls to 9,432 k€, that is roughly the third part of total cost faced in Case B, where DG facilities (renewables and GmT) have been installed but final customers rely on energy distributors to cover further energy needs. Moreover, it has to be remarked that exploiting GmT by purchasing gas from the market is less convenient than purchasing electric energy in electricity market.

TABLE II
ACTUALIZED COST OUTLINE [k€]

		PV	WT	GmT	Grid
Case A	Installation costs	---	---	---	---
	Operation costs	---	---	---	40,594
	Revenues	---	---	---	---
	Cost per facility	0	0	0	40,594
	TOTAL COST	**40,594**			
Case B	Installation costs	5,100	1,590	1,113	350
	Operation costs	789	710	24,743	2,238
	Revenues	5,448	3,028	---	50
	Cost per facility	441	–728	25,856	2,538
	TOTAL COST	**28,107**			
Case C	Installation costs	5,100	1,590	---	220
	Operation costs	789	710	---	9,549
	Revenues	5,448	3,028	---	50
	Cost per facility	441	–728	0	9,719
	TOTAL COST	**9,432**			

VI. Conclusions

In this paper, a methodology for the economic evaluation of a microgrid has been addressed, focusing on electricity sector. The procedure aims to minimize costs, allowing the integration of DG facilities, in order to cover the electricity demand of a defined set of final users over a selected time horizon. The procedure has been applied to a realistic system, representing a cluster of loads in the residential sector placed in Apulia region in Southern Italy, and accounting for photovoltaic systems, wind turbines and gas microturbines as available technologies for local generation. Different solutions have been investigated, concerning supplying conditions for electricity and natural gas, and taking into account support policies currently in force in Italy. Results have proved that the installation of a microgrid, under the defined conditions, can be convenient, especially if renewable-based technologies are exploited. Moreover, if electric energy and natural gas distributors provide for microgrid energy needs, the use of microturbines has revealed convenient to generate electric energy locally. Whereas, if the microgrid manager decided to play in energy market both for electricity and gas purchasing, installing microturbines has turned to be unprofitable compared to withdrawing power from the grid at market price.

This perspective is limited to the management of electricity end-use so far. Further improvements can be applied to the procedure in order to take into account direct exploitation of thermal energy coming from local generators, such as gas microturbines or solar thermal installations, for final uses. Moreover, the behaviour of microgrid in the presence of suitable storage systems can be assessed, and these systems will be designed in the global aim of optimizing costs. Another aspect that can be investigated is the ability of microgrids to provide for regulation services to distribution grid and improvements for power quality involvements, and convenience of investing in microgrids for this purpose.

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VIII. Biographies

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