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11,8-100% Rural Renewable Energy and Power Supply and its Influence on the Luxembourgish Power System

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Abstract

Currently, the majority of countries tries to reduce their dependency on fossil fuels by the introduction of renewable resources in their energy systems. In the following the relatively small Luxembourgish electricity system is analysed (0.55 Mio Inhabitants). Current power-system-models mainly focus on larger systems, due to the unavailability of specific consumption-data. Prices and effects on the Luxembourgish power system of different supply scenarios for rural-private households are analysed. A linear optimisation for the minimum-cost of the power-supply of a village with the following renewable energy resources: wind- (max.100kW), solar-PV- and hydrokinetic-power is made. The electricity-demand scales with the number of inhabitants and agricultural-consumers. The wind-power-potential differs with the location of the village. The solar-radiation is assumed to be the equal over the country, due to the small size of approximately 80 by 50 km. The hydrokinetic turbines complete the supply where a village is located close to a river. The minimum cost of the specific village power-supply is the result of the optimization. The installation- and maintenance-cost of each renewable technology are considered. The whole number of a rural Luxembourgish model villages private households is considered and their electricity contribution to the system is estimated for different renewable energy supply scenarios, namely from 20% to 100% renewable-energy-scenarios. For each scenario the power exchanged from the village to the grid is calculated in 15-min-steps for 9-years, the amount differs widely with the number of applied generation technologies. Due to the high share of imported electricity of about 80% in the recent years, every consideration of national power generation does not harm the supply security. Luxembourg is a good model country to analyse the high share of distributed, renewable generators, due to its structure of rural and civic regions and their effects on a central European region with a high electricity-consumption.

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1. Introduction

The share of renewable generated electricity increases within the European energy system. Analysing the electricity demand of private household's two characteristic regions can be distinguished, on the one hand cities and large settlements, on the other hand rural areas. Observing the power system an important differences between the regions is the private energy demand, which is directly linked to the number of inhabitants and the variable population density, as well as the available space to install renewable generators. In this publication a renewable supplied sample village, representing an average Luxembourgish rural settlement is analysed. The load curve of the Luxembourgish sample village is developed, consisting of standardized load profiles describing the characteristic power demand of the different household, agricultural and service consumer. In a second step a potential analysis was made to predict the solar photovoltaic (PV), small wind power and hydrokinetic potential of the sample village. Considering the reduction of the installation cost of the renewable plants an optimum generation park was derived. Three renewable energy supply scenarios, namely 11.8 %, 30 %, and 100 % of annual electricity demand are discussed.

2. Methodology

In this paper the energy demand of the rural population of Luxembourg is analyzed and several renewable supply scenarios for the settlements are proposed. About 36 % of the population lives on the countryside [1,2]. Settlements with less than 2000 inhabitants are considered to derive a model village's size. Once the demand is derived three different renewable technologies are discussed to cover the village's energy demand. Using historical national generation data of the three renewable technologies for nine years, an optimization problem is defined to analyze the different renewable scenarios to find the lowest cost solution consisting of solar-, wind- and hydro-power plants. In a last step the contribution of a novel hydrokinetic turbine to a villages 100 % renewable energy supply is presented and analyzed.

3. Results

3.1. Village Size and Energy Demand

It can be seen in figure one, that the number of small settlements is higher than the number of large settlements in Luxembourg. Figure one includes 91 % of the Luxembourgish settlements with a number of 187 064 inhabitants which represents 36.5 % of the 512 353 inhabitants in 2012. The median of the number of village inhabitants is 255, the arithmetic average is 415. Considering the median as more representative, in the following the energy demand for a village of 255 inhabitants is analysed.

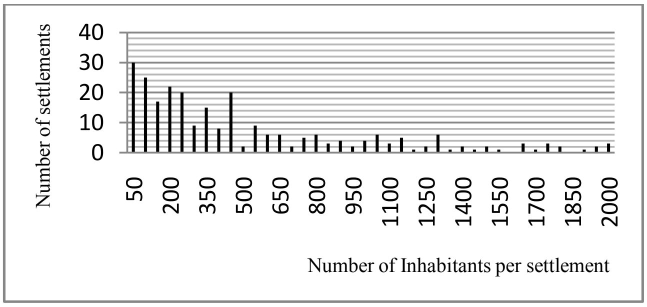

Figure 1: Size distribution of the Luxembourgish villages, median indicated by red bar.

A private household is defined in this publication as, 2.7 inhabitants per household with an annual electricity demand of 3350 kWh, the value is interpolated from the data given by the BDEW [3]. The BDEW load profile HO is used to characterise the household's power demand.Apart from the private households the following consumer are included in the energy analysis, agricultural consumer, small industrial and services consumer.

To represent the average Luxembourgish power demand, the average number of farms per village was derived from national statistics. Furthermore, the average number of employees per farm is used to derive the specific energy demand [4]. Taking into account that the employees might be part-time employed the annual working hours per farm are transformed in annual working units. Assuming in average 2.4 employees per farm (part time), it leads to 1.8 full time worker. In average 6397.6 kWh are assumed per full time worker of a farm. Considering the average 1.2 farms per 100 inhabitants 3.06 farms per village are assumed which leads to the demand mentioned above. Again a BDEW load profile with the LO specification is used for an annual agricultural energy demand per village of 35 238 kWh.

The small industrial and service consumers' energy demand is derived from the average number of employees per domain in the Luxembourgish villages [5,6]. Matching BDEW load curves to the different "Nomenclature statistique des activitéséconomiquesdans la Communautéeuropéenne" (NACE) profiles characterizing each service domain, while comparing those to the German definition of economy branches ("Definition der Wirtschaftszweige") the following BDEW load profiles are used: G1, G2, G4, G5, see table one.

Table 1: Energy demand of the rural Luxembourgish industrial and services consumers.

	Number of worker in rural Luxembourg	BDEW Profile	Energy [kWh/worker]	Energy [kWh/100 inhabitants]
Construction	4250	**G1**	1203.6	12564.9
Offices	3380	G1	1987.5	
Production Companies	1095	G1	3742.1	
Trade and Commerce	9560	**G4**	5501.6	28817.3
Hotels and restaurants	4005	**G2**	4406.8	9434.9
Food companies	370	G4.**G5**	7285.7	740
Laundry services	40	G1	6860.5	

Due to the high energy demand of large industrial consumer, their existence within the model village is neglected since these companies are rarely located in rural villages [7].Hence, the community halls power consumption as well as the street lights electricity demand are neglected, due to their small influence compared to the consumer mentioned above [8].

Finally, the power demand curve of the village consisting of the BDEW load profiles mentioned above varies between 105.9 kW at a January morning and 19.2 kW on a Sunday morning in September. The average consumption is about 55 kW with an annual electricity demand of the model village of 481.61 MWh,see figure two.

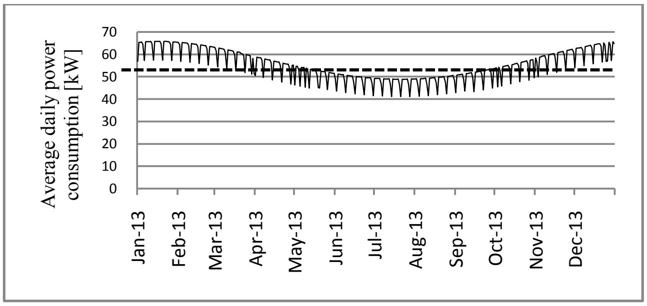

Figure 2:Daily average model villages load curve for one year with the average power demand (dotted line).

3.2. Renewable Generators and Dimensions

In the following the renewable generation of wind- and solar-photovoltaic power plants is analysed and its potential to supply an average Luxembourgish village is derived. The following assumptions were made for the technologies.

Solar - Due to the decentralized character of the study only private houses are considered for solar systems. Therefore, the size of the considered solar plant is restricted by the average rural house size and the related roof size, as well as of shading effects due to the roof form. 95 % of the rural households are located in detached family houses. The average rural detached family house has a size of 280 m² [9]. The roof sizes of all Luxembourgish houses is about 21.3 Mio m² distributed on 127000 buildings, which yields to a size of 168 m² per house [10], including any kind of building. It is assumed that in the cities several households are located in apartment buildings as well as more administrative buildings exist which balances the average size of the roofs, whereas on the countryside more single family homes and less administrative buildings exist. Therefore, using the number from 2001 of 171 953 households nationwide, we get an average roof size of 124 m² [2]. Expecting in average two levels for a rural detached family home this number matches quite well the household size of 280 m². Assuming a loss of roof size due to shading effects the available size is reduced by 28 % [11]. The houses orientation of the roofs varies with the following values, North-South 49.8 %, East-West 44.3 % and flat roofs are 5.8 % [12]. It is assumed that the solar systems on flat roofs are oriented in Southern direction. Due to the orientation losses, the size is reduced again by 33 %.

$$f_{Orientation} = (0{,}5 * 0{,}498 + 0{,}058 + 0{,}82 * 0{,}443) \approx 0{,}67$$

Finally, the mismatch between solar module form and roof is taken into account by a further reduction of the useable roof size of 20 %. Furthermore, the module degradation is taken into account by $f_{deg} = 0{,}926$ [13]. Finally, the useable potential is reduced on 38.6 % of the theoretical potential. Calculated for a global annual radiation harvest 1043 kWh/m² in Luxembourg[5]. The simulation of the radiation was made for the village Levelange, the Satellight data was used which is based on the half-hourly data of METEOSAT with a sufficient resolution of 5 x 7 km²[12]. A PV system of 8.5 $kW_p$with a size of 56m² per household was simulated.

Wind - As the second technology small size 100 kVA-wind energy converter are analysed. At first a maximum number of turbines per village is derived, to predict their potential contribution. The size is limited to 100 kVA to ensure that the turbines can feed into the low voltage 400 V network and balance the power demand directly on the consumer level. A formula is derived to predict the maximum number of turbines depending on the number of inhabitants of a village and the population density. The population density is in rural areas 150 inhabitants/km² [14]. The model village has therefore a size of 1.7 km². Seeing that Luxembourgish villages are mostly located around street crossings a circular shape of the village with a radius of 736 m is assumed. To limit the noise disturbance of the population an acceptable level 35 dB is assumed for the first inhabitants of the village following the German law for night-time noise emission levels [15-17]. For an average 100 kVA turbine, an emission of 95 dB is used to calculate the needed distance between turbines and settlement [15]. Using the formula,

$$r = r_0 * 10^{\left(\frac{L_S - L_r - 11dB}{20dB}\right)}$$

withL_s the sound pressure level at the source and L_r the level in the distance r. A minimum distance of 282 m is derived. The plants have to be installed in the South West of the village to harness the wind mainly coming from that direction during half of the year (49.3 %) [18]. Using the following formula,

$$N_{Turbines}\,(N_{Inhabitants}) = \frac{1000\frac{m}{km} * \pi}{6 * 25{,}4} * \left(\sqrt{\frac{N_{Inhabitants}}{150\pi}} + 0{,}282\right)$$

the number of turbines can be derived to 21, using an average distance of six rotor diameters between the turbines on the radius [10]. To derive the theoretical energy generated by each turbine the ground roughness and the turbine height has to be taken into account. With the following formula,

$$v_h = v_0 * \left(\frac{h}{h_0}\right)^g$$

The exponent g = 0.28 is chosen for an open space with obstacles up to 15m. Using the average wind speed data available for Luxembourg the wind speed for the turbines with a height of 35 m is derived [19,20]. Using the Findel airport wind-real-time measurements of the past nine years in a 15 min resolution a dynamic wind profile is derived for the model village. An average wind velocity for Luxembourg of 5 m/s in a height of 30 m is derived from [10], which is confirmed by the European wind atlas [21]. For a turbine of 35 m 5.22 m/s are derived for a roughness coefficient for agricultural areas of 0.1 and a Weibull factor of 2, 1839 full-load hours are derived for the considered turbines.

Hydrokinetic turbines will be considered in this publication to evaluate their influence on the villages' energy exchange with the power grid. As for the wind power- and solar-systems, regional limitations of the number of systems in the vicinity of the village are derived.

The number of hydrokinetic turbines is limited by the rivers size and the losses in the low voltage network, which are after the BDEW 2% of the feed in voltage [22]. Therefore, a maximum length of the lines is calculated connecting the turbines with the grid by a copper cable of 3 x 120 mm², 23 serial connected turbines with a maximum power output of 20 kW each and an average output of 780 W, can be placed around the sample village.

Considering historical hydrological data, their output varies between summer and winter time, in the winter period the average power output is about 1400 W and in the summer half about 50 W. Therefore major contributions of the power generation in the winter half are expected, to reduce the villages' increased power import from the grid, see figure 2.

3.3. Cost Analysis

A private consumer pays in Luxembourg about 16.46 ct€/kWh in 2013, consisting of 7.31 ct€/kWh network charges, 1.18 ct€/kWh taxes/other charges and 0.99 ct€/kWh value added tax. Finally, 6.98 ct€/kWh costs the generation of the Luxembourgish electricity. The electricity price per kWh reduced from 17.05 ct€/kWh in 2012 [23]. In the following the annuity method "VDI-Norm 2067" will be used to calculate the specific generation cost for the three different technologies [24, 25]. Using the following formula,

$$\dot{K} = \sum_j \left[\frac{i * (i+1)^{n_j}}{(i+1)^{n_j} - 1} * k_{P,j} * P_N\right] + \dot{K}_B$$

With $\dot{K}$ as the annual cost, i is with 2.5 % the specific Luxembourgish interest rate for energy system investments [26], j the sum coefficient for the different plant components of differing consideration timespan, n the considered timespan in years, $k_{P,j}$ the specific plant generation cost in €/kW, P_N the rated power of the plant, $\dot{K}_B$ the maintenance and insurance cost. Table two to four specify the systems cost for each renewable technology. Table five shows the average annual system cost and generation per technology.

Table 2: Cost for a PV roof system of 5-10 kW in Luxembourg, after consultation of local supplier.

Component	Lifespan	Cost
Solar Panel (250Wp)	25 years	192.00 EUR/panel
Inverter (SMA STP 8000TL-20)	13 years	2058.00 EUR/piece
Grid connection (distance 150m)	30 years	198.00 EUR fix
Spare parts	-	34.00 EUR/panel
Insurance and taxes	-	37.50 EUR/panel
Maintenance	-	42.50 EUR/panel
Maintenance and Insurance	-	240 EUR fix

Considering a time span 13 years the annuity is 972.30 EUR/a for an 8,5kWp system.

Table 3: Cost of a 100kVA-wind turbine [27].

Component	Lifespan	Cost
Turbine and tower + Installation and transport	30 years	230 000 EUR + 25 000 EUR
Foundation	60 years	50 000 EUR
Grid connection (distance 150m)	30 years	15 000 EUR
Spare parts	30 years	8000 EUR
Insurance and taxes	-	1150 EUR
Maintenance	-	3500EUR

Considering a time span 13 years the annuity is 20976.79 EUR/a for a 100 kVA system.

Table 4: Cost of the 20kVA hydrokinetic turbine [28-30].

Component	Lifespan	Price
Entire System	30 years	22730 EUR
Generators	17 years	3842 EUR
Inverter	13 years	4882 EUR
Roller bearings	15 years	800 EUR
Annual Maintenance	-	450EUR/a
Insurance	-	113.65 EUR/a

Considering a time span 13 years the annuity is 2129 EUR/a for a 20 kW system.The specific generation characteristics of the three technologies can be seen in table 5.

Table 5. Generation specifications of the three renewable technologies supplying the model village.

	Photovoltaic	Wind power (average speed in 35m)			Hydrokinetic
		3.92 m/s	5.22 m/s	6.59 m/s	
Rated power	8,5 kWp		100 kVA		20 kVA
Annual full-load hours [h]	817.9	1165.0	2185.7	3453.1	340.3
Energy generation [kWh/a]	6952.3	116 501.4	218 574.9	345 309.9	6806.6
Generation cost [EUR/kWh]	0.140	0.181	0.096	0.061	0.313

3.4. Optimization

The cost optimization aims on a minimum cost to supply the villages' electricity demand. A minimal cost solution for the considered time span of 9 years is derived. Finally, the most inexpensive solution, consisting of a number of PV systems and wind energy converter is presented. In a second step the influence of the hydrokinetic turbines on the optimization is shown and evaluated. The global linear optimization is defined as followed,

$$\min_{x \in \mathbb{N}_0} \{ c^T x \mid Ax \geq b \}$$

$$Ax \geq b = \begin{bmatrix} P_{solar,1} & P_{wind,1} & P_{hydr,1} \\ \cdots & \cdots & \cdots \\ P_{sol,m} & P_{wind,m} & P_{hydr,m} \end{bmatrix} * \begin{bmatrix} x_{solar} \\ x_{wind} \\ x_{hydr} \end{bmatrix} \geq \begin{bmatrix} P_{Demand,1} \\ \cdots \\ P_{Demand,m} \end{bmatrix}$$

$$c^T x = \begin{bmatrix} x_{sol} \\ x_{wind} \\ x_{hydr} \end{bmatrix}^T x$$

Here, the expression Ax is understood component wise, so that the left hand side can be written as followed,

$$a_t x = \sum_{i=1}^{n} [a_{i,t} * x_i] = \sum_{i=1}^{3} [P_{i,t} * x_i]$$

The right hand side is the energy demand of the sample village $P_{Demand,t}$ for each time step t. The cost function which has to be minimized can be written as,

$$c^T x = \sum_i (c_i * x_i) = c_{solar} * x_{solar} + c_{wind} * x_{wind} + c_{hydr} * x_{hydr} \rightarrow min$$

In the scenarios discussed in this publication three different energy demands have to cover by the renewable generators. Therefore, a secondary condition has to be defined for the optimization. The different renewable plants have to generate within one year as much or more energy than consumed,

$$p * E_{Load} \leq E_{Solar} * x_{Solar} + E_{Wind} * x_{Wind} + E_{Hydro} * x_{Hydro}$$

Here p is the share of renewable supplied energy for each scenario and E_{Load} the annual villages' energy demand, E_{Solar} / E_{Wind} /E_{Hydro} are the specific energy amounts generated per technology (see table 5) and x the number of plants of each technology.

4. Discussion

In the following three different renewable energy scenarios are defined and the number of renewable generators needed to meet the electricity demand is derived. The village consist of 255 inhabitants in 94 households supplied with a possible maximum number of 94 solar PV plants with 8.5 kWp each and a maximum of 21 wind power plants with a maximum of 100 kVA each in the simulation. A novel oscillating foil hydrokinetic turbine is included in the optimization to show its influence on the villages' energy autarky. The scenarios are as followed,

- 11.8 %: Luxembourgish Goal for 2020 [31],
- 30 %: European goal for 2030 [32],
- 100 %: Theoretical energy goal for a renewable supply.

Furthermore, the solutions are calculated for three wind speed classes, namely, 3.92 / 5.22 / 6.59 m/s, these are the three interpolated main velocity groups shown of the Luxembourgish average wind velocity map [19].

Comparing the results of the three scenarios it can be seen in table six that none of the scenarios leads to an entire autarky of the model village from the grids energy supply. A second finding is that the energy supply is mainly based on solar PV plants for energy supply scenarios with a lower renewable share, just starting from the 100% renewable energy and the mean wind speed scenario, wind power plants are beneficial in the generation setup. It can be seen that with a high share of renewable generators also the excess power increases, comparing the two 100% scenarios of minimum and maximum wind speed, it can be seen that the excess peak power reduces from 650 kW to 234 kW when a wind turbine replaces the generation of 50 solar plants in the latter case. Furthermore, the annual time share of the generation directly matching the electricity demand increases from 28.1 to 44.1 %, the energy autarky of the settlement increases.

4.1. Influence of the Hydrokinetic Generators

The influence of the hydrokinetic turbine is positive from an energetic point of view. Comparing the 100% renewable solar supplied village with the solar and hydrokinetic scenario, the excess power peak reduces from 650 to 632 kW, which is still higher compared to the setup including a wind power generator. The systems autarky increases with this setup of 47 PV plants and 23 turbines instead of 70 PV plants, from 28.1 % to 30.3 %.

Table 6. Optimization results for the three "energy scenarios".

Scenario (Wind speed)	11.8% (mean)	30% (mean)	100% (min.)	100% (mean)	100% (max.)	100% with Hydro-kinetics
PV-Systems [-]	9	21	70	4	20	47
Wind turbines [-]	0	0	0	2	1	0
Hydrokinetic [-]	0	0	0	0	0	23
Annual energy production [MWh]	62.57	146.00	486.66	484.63	484.35	483.31
Energy balance [MWh]	-419.65	-336.22	4.44	2.41	2.13	1.09
Direct energy consumption [MWh]	62.52	130.12	207.43	259.91	313.45	235.44
Annual deficit for only directly consumed electricity [MWh]	419.7	352.10	274.79	222.31	168.77	246.77
Excess energy for direct consumption [MWh]	0.05	15.88	279.23	224.72	170.89	247.86
Max. Residual load (Import) [kW]	105.9	105.9	105.9	105.8	105.8	105.6
Max. Excess power (Export) [kW]	27.6	144.3	650.1	183.1	234.0	632.2

Power directly supplied[%] (share of a year)	0.1	8.6	28.1	34.8	44.1	30.3
Annual Energy supply [%]	13.0	30.3	100.9	100.5	100.4	100.2
Generation cost [EUR/kWh]	0.140	0.140	0.140	0.095	0.084	0.196

5. Conclusion

In this paper the size of an average rural settlement in Luxemburg was statistically derived. Therefore, the median of the number of inhabitants of all the villages was considered. For this median size of 255 inhabitants the average electricity consumption and the villages load curve, including the agricultural and service sectors' consumption, as well as the households demand was designed using BDEW load profiles. Once the demand is specified, different renewable energy supply scenarios were developed, using wind-, solar- and hydrokinetic-power generation. Three scenarios were considered named after the annual renewable energy generated for each, namely the 11.8 %. 30 % and 100 % scenario. A maximum number of generators for each technology was derived, limited by the roof size for the PV plants, the population density, village size and noise emission for the wind power plants and line voltage drops limiting the number of hydrokinetic turbines around the village. So, a maximum installable number of 94 solar plants, 23 wind- and the same number of hydrokinetic-turbines is derived for the model village.

It can be seen that for higher shares of renewably generated energy wind turbines become financially more beneficial than the solar systems. The 11.8 %, 30 % and 100 % (low wind) scenarios consist of only solar PV systems, therefore the price has a constant value of 14 €ct/kWh. Starting from the 100 % (middle wind) scenario the price reduces to 9.5 €ct and 8.4 €ct for the high wind speed scenario. Replacing 23 solar plants in the 100 % scenario by the same number of hydrokinetic turbines the generation price per kWh increases from 14 to 19.6 €ct.

Comparing the generation cost of the renewable systems with the 2013 generation cost within Luxembourg of 6.98 €ct, it can be seen that for the high wind speed scenario the price difference is just 1.42 €ct compared to the 2013 private electricity price. Assuming that additional charges of 9.48 €ct per kWh were paid in 2013 from the private customers, a 100 % renewable supplied village with 20 solar plants and one wind energy converter leads to price increase of 8.6 % on 17.88 €ct. Using the most expensive setup with the hydrokinetic turbines a price of 29.08 €ct/kWh has to be paid, which is an increase of 77 %. Compared to the electricity price of Germany in 2013 it is not even 1 % higher (28.84 €ct/kWh in 2013 [33]). It has to be kept in mind that just the rural energy demand consisting of private services- and agricultural-consumer is covered excluding industrial electricity consumption.

6. Acknowledgement

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