Optimizing the use of renewable energy sources in the energy mix of Hungary

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***Abstract*— This paper reports short-term energy scenarios for the heat and electricity generation in Hungary, considering the recent developments in the overall European and national energy policy framework promoting the use of energy from renewable energy sources. Focusing on the heating and electricity sectors, a methodology for portfolio optimization has been developed in order to identify the optimal energy mix in terms of technology alternatives and energy sources. As a base case, a pure economic assessment was done considering the investment costs, the net present values and the operation and maintenance (O&M) costs. The optimization was extended by involving additional factors in the next steps, adding carbon prices and the external costs of the environmental and human health (physiological) impacts to the model. An aggregate approach is applied to reduce complexity; national aggregation was chosen for the electricity sector while building typological groups and local geographical entities were defined for the heating sector. The level of saturation of different technology alternatives in the market is modeled in the proposed methodology, as well. The mathematical formulation of the optimization problem was given as a non-linear case of the distribution problem.**

Keywords—optimal energy mix, nonlinear programming, distribution problem

I. INTRODUCTION

Since the adoption of Directive 2009/28/EC on the promotion of the use of energy from renewable sources, the opportunities and constraints for increasing the share of renewable energy sources in the supply and energy mix optimization have remained key issues in Hungarian energy policy. According to the National Renewable Energy Action Plan 2010-2020 (NREAP) of Hungary, the country has committed to reach the overall target of 14.65% as the share of energy generated from renewable sources in gross final energy consumption by 2020, covering the electricity, transportation and heating and cooling sectors [1]. For the next decade, a more ambitious development is foreseen to ensure the key role of renewable energy sources in meeting the energy needs. In 2014, the member states agreed to reach a share of at least 27% in the final energy consumption of the European Union by 2030, as part of the energy and climate goals of the European Union [2]. In June 2018, a new European Union-Wide binding renewable energy target of 32% was defined for 2030 (with a clause for an upwards revision by 2023) by a political agreement that needs to be formally adopted by the European Parliament and the Council. Therefore, well-founded methodological approaches are required the address the problem of the complementary national energy policy frameworks and national renewable energy roadmaps.

While the electricity, heating and cooling sectors are closely interrelated by the co-generation of heat and electricity, and their assessment requires a uniform, harmonized methodology, the assessment of the transportation sector can be conducted separately, as it relies on different fuels and energy carriers at present and in the near future.

The purpose of the present study is to develop an ideal heat and electricity generation portfolio based on renewable energy sources, relying on the specific energy costs available from the literature, and on regional (county-level) energy potential and heat demand data [3]. Among these factors, we need to highlight the importance of the specific energy costs where rather large intervals are possible depending on the site-specific local conditions of the investments. In the model developed for our study, the uncertainty of costs was considered by increasing the specific costs in parallel to the saturation of the market; we simulated in this way that the sites having the most favourable conditions are selected for the investments at first [4].

In the mathematical definition of the presented problem, we considered the level of saturation of the market by linear functions; i.e. initially, all technology alternatives are installed where the most favourable conditions are available, and after that, they become gradually less competitive as a function of the generation capacity already installed.

The search for an optimum defined in this way results in a nonlinear programming problem.

II. METHODOLOGY

In our research, we focused on the portfolio optimization of the national renewable energy sources in the heating and electricity sectors. When defining the key optimization problem, we ignored the existing power plant portfolio as a starting point; and considered an ideal energy mix as the target of a potential roadmap. In the calculations underlying the target scenario, we preferred an economic approach, taking into account the specific costs of the individual energy generation alternatives, the *LCOE* (levelized cost of electricity for the average lifetime) which can be calculated from the formula:

$$LCOE = \frac{\sum_{i=1}^{n} \frac{I_i + M_i + F_i}{(1+r)^i}}{\sum_{i=1}^{n} \frac{E_i}{(1+r)^i}},$$

where

I_i: investment cost in year *i*;
M_i: operation and maintenance (O&M) cost in year *i*;
F_i: fuel cost in year *i*;
E_i: energy generated in year *i*;
n: lifetime and
r: discount rate.

As supplementary calculations, the optimization was also done by considering the carbon prices and the external costs of the environmental and human health (physiological) impacts [5]. Assumptions on realistic investment and O&M costs were made based on the evaluation of benchmark projects [6]. As shown by the project experiences, the costs exhibit a large variation in the range [c_{min}; c_{max}], heavily influenced by the site-specific physical conditions and the closely interrelated number of full load hours. In the mathematical definition of the presented problem, we considered the level of saturation of the market by linear functions; i.e. while all technology alternatives are installed at the most favourable locations and techno-economic conditions at first, they become gradually less competitive as a function of the generation capacity already operating.

The mathematical formulation of the optimisation problem was provided as a distribution problem [7] with convex, nonlinear objective function. Four sets were created for an exact definition of the problem:

- E as the set of the renewable energy sources, |E|=m;
- A as the set of technology alternatives in the heating and cooling and electricity sectors by size ranges, |A|=k;
- T as the set of building typological groups [8] for the definition of heat and hot water demand, |T|=t;
- L as the set of local geographical entities, |L|=s, since both the heat demand and the available potential of renewable energy sources [9] were assigned to geographical entities in the calculations.

Based on the initial sets listed above, the following functions and relations were established:

- *g*: A→E as the function of the energy sources belonging to the alternatives, i.e. a single energy resource is assigned to each energy generation technology. In our calculations, also the converse relation of function *g* has a role where $\left\{g^{-1}(e_i)\right\}$ is the set of alternatives belonging to energy resource *i*.
- *f*: A→T as the building type function belonging to the technology alternatives. The size ranges of the energy generation technology options have been defined so that they can enable the supply of a given building typological group. The converse relation of function *f* is $\left\{f^{-1}(t_i)\right\}$, i.e. the set of technology alternatives belonging to the building typological group *i*.

Two parameter matrices defined on the basis of the geographical entities contain the data that are necessary for a quantitative evaluation:

- P_{sxm}: as a matrix consisting of real numbers (where the rows correspond to the local geographic entities and the columns refer to the energy sources), quantifying the local potential values, i.e. the potential of the renewable energy sources available at the geographic entity.
- H_{sxt}: as a matrix consisting of real numbers, quantifying the local heat demand and the hot water demand of the individual building typological groups, considering the currently existing set of buildings.

It should be noted that a global approach can be used for the electricity demand, as it can by more easily transported in comparison to the heat. Like the parameters, also the variables were arranged and handled in a tabular form. When searching for an optimum, we aim to find the energy quantities assigned to the technology alternatives on a local scale that is symbolized by the matrix V_{sxk}. For each v_{li} value belonging to a solution, the sum of each column *i* equals to the amount of the global energy generated by the technology alternative *I*, i.e. $\forall i \in [1;k] \quad \sum_{l=1}^{s} v_{li}$. We receive the total annual energy production by summing up the amounts of the global energy generation per energy source $\sum_{i \in \{g^{-1}(i)\}} \sum_{l=1}^{s} v_{li} = w_i$. For a more compact form of the objective function, also the *m* number of w_i values is introduced as a variable, neglecting the fact that the number of constraints is increased. Similarly, also for the co-generation of heat and electricity, where the alternatives *j* and *i* are operating simultaneously, we introduce three variables. For the technologies suitable for co-generation $\left\{cog(j;i)\right\}$, we introduce three variables for each local region *l*; these are the locally generated heat v_{lj} and electricity v_{li}, and additionally q_{lji} as the deviation from the optimal ratio of cogeneration $h = \frac{v_{lj}}{v_{li}}$; where the value of *h*=0.3 considered as the optimum. The introduction of this third variable where $q_{lji} = v_{li} \cdot h - v_{lj}$ is necessary to handle the additional cost of a less efficient operation. At most co-generation technologies, it is possible to generate electricity only, but this can be realized at a lower efficiency, i.e. higher specific cost. The additional cost of inefficient operation was considered by the quadratic formula $d_{ji} \cdot q_{lji}^2$ in the objective function, where the nonnegative coefficients d_{ji} represent the standard cost of deviation.

The supply constraints belonging to the distribution problem can be defined by the local potentials:

for $\forall i \in [1;s]$ and $\forall j \in [1;m]$ $\quad \sum_{a \in \left\{g^{-1}(j)\right\}} v_{l_i a} \le p_{l_i j}$, (1)

while the generation constraints belonging to the electricity and heat demand can be given by building typological groups:

for $\forall i \in [1;s]$ and $\forall j \in [1;t]$ $\quad \sum_{a \in \left\{f^{-1}(j)\right\}} v_{l_i a} \le h_{l_i j}$. (2)

However, the binding target regarding renewable energy generation needs to be fulfilled: $\sum_{i=1}^{m} w_i = Q$ (3)

Considering also the non-negetivity constraints:

$0 \le v_{li}$, $0 \le w_i$ és $0 \le q_{lij}$ for each $l \in L$, $i \in A$ and $j \in A$

The cost coefficients in the objective function are defined by the mean values of the linearly increasing prices:

$$\overline{c_a} = \frac{1}{v_j}\int_0^{v_j}\left(c_{a\min} + \frac{c_{a\max} - c_{a\min}}{p_j}\, y\right)dy \qquad (4)$$

and in this case,

$$\overline{c_a} = c_{a\min} + \frac{c_{a\max} - c_{a\min}}{2p_j} v_j$$

$$\text{where} \quad p_j = \sum_{l=1}^{s} p_{l_i j} \quad \text{and} \quad v_j = \sum_{l=1}^{s} \sum_{a \in \{g^{-1}(j)\}} v_{l_i a} ,$$

the value of the objective function can be computed by the formula:

$$\sum_{l=1}^{s}\left(\sum_{a=1}^{k} \overline{c_a} \cdot v_{la} + \sum_{(j;i) \in \{cog(j;i)\}} d_{ji} \cdot q_{lji}^{\;2}\right) = z(\min) \qquad (5)$$

The described quadratic problem (1)-(5) is convex due to the nonnegative cost coefficients; however, as there are about a thousand of variables, a strong optimization tool is required. Our optimization model was built and solved in a GAMS environment [10], a high-level modelling and solving system for mathematical optimization. The optimal solution of the defined NLP problem provides an ideal portfolio of the heat and electricity generation alternatives.

III. Results

The purpose of the present work was to develop an optimal national portfolio of the renewable energy sources. We assumed a total gross energy consumption of 760 PJ for Hungary for 2020, 75% of which belongs to the electricity and heating sector. In the two sectors, a total energy of 97.5 PJ needs to be supplied by using renewable energy sources. Energy generation alternatives were divided into three main categories. Wind, hydro and solar units are within the electricity-only generation category resulting in nine alternatives when considering the size ranges at the same time [11]. In the co-generation category, the heat is supplied by biomass, biogas, waste or geothermal energy; there are ten alternatives in this category in total. Further seven alternatives were assigned to the heat-only generation category as only heat supply is possible when using solar irradiation, geothermal energy or biomass combustion. The constraints of the distribution problem are defined by the county-level heat demand of the building typological groups and by the county-level renewable energy potential estimates in addition to the annual electricity demand [12] (Table 1).

As a first approximation, the coefficients of the objective function were calculated from the specific costs. The extrema of the specific costs define very large intervals (Table 2) where doubled or tripled prices can appear. Instead of using a simple mean value, the use of intervals can provide valuable additional information regarding the actual market environment.

The limited total national sustainable potential (209.5 PJ) is the double of our commitment for 2020; this enables a narrow range only for developing the energy mix. With respect to the moderate reserves present in the system, several alternatives are limited by the constraints. If only economic aspects are considered, wood and agricultural biomass has a share of 65 PJ in the optimal portfolio because of the large amount and high heat demand of single-family houses and the availability of biomass (Figure 1).

The other renewable energy sources are more or less evenly represented, only the solar PV systems are excluded from the portfolio due to their high specific cost. It is interesting to observe in the energy mix obtained from the model that only one energy source (sewage biogas) exploited fully the available potential.

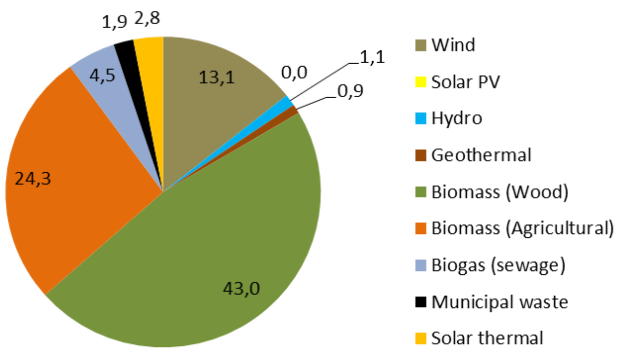

Figure 1: Optimal national portfolio of renewable energy sources with respect to economic impacts only

Energy demand per category	Electricity demand	Heat demand Single-family house	Heat demand Medium-scale multi-flat building	Heat demand Large-scale multi-flat building
PJ	197.6	283.7	49	40

Table 1: Electricity and heat demand estimates per building typological group for 2020 [4]

	Wind	Solar PV	Hydro	Geothermal	Biomass	Biogas (sewage)	Municipal waste	Solar thermal	Heat pump
PJ	14	7	1.3	6.1	149	4.5	2.2	10.6	15
€/MWh	61.4	110.8	77.7	30.6	44	26.1	85.5	35.3	30.6
€/MWh	152.6	224	118.4	100.7	108.6	34.9	115.2	69.2	69.2

Table 2: National values for the sustainable potential of renewable energy sources, lowest and highest values of the specific costs irrespective to technology and size ranges [9] [4]

		Wind (onshore)	Solar (PV rooftop)	Hydro (small)	Geothermal power plant	Biomass (wood)	Biomass (agricultural)	Solar collector
Human health impact	Ec/kWh	0.09	1.00	0.09	0.98	1.15	2.86	0.48
Climate impact	g CO_2eq/kWh	12	46	4	45	18	18	22

Table 3: Quantified impact on human health and specific CO2 emissions [13] [14]

At a pure economic approach, the average energy cost is stabilized at 6.71 c€/kWh.

The idealized view that renewable energy sources have no negative impacts at all is shared by many people. However, it is hardly true that renewable energy generation is free of environmental, human health and climate impacts; similarly, it is wrong to assume that these impacts would be the same in cases of different technologies. In our model, we considered the external costs to human health as a receptor, by applying an impact pathway assessment, based on a specific emissions dataset taken from the life cycle analysis carried out in the framework of the CASES project [13] that used the reference year of 2020 for technologies. While the energy generation as such has the largest contribution to the negative impacts in cases of fuel cycles that are based on combustion, but for most of the renewable energy sources, we need to consider the environmental and human health impacts during the whole life cycle (manufacturing of the power generation equipment, transportation, fuel supply, construction and decommissioning of the power plant) to have a realistic view. The comparison of the climate impacts is based on the specific emissions of greenhouse gases [14].

Of course, the contribution of the climate impacts of renewable energy sources is negligible to the costs, even if we assume a carbon price of 17 €/tCO2 that is significantly higher than average carbon price at present. The consideration of the external costs does not result in substantial restructuring in the optimal portfolio. The ratios of the energy sources are slightly modified, and there are two new energy sources (hydro, wind) that fully exploit the national potential (Figure 2). The moderately decreasing use of biomass can be explained by the harmful emissions of the individual heating and the closely interrelated, increasingly negative impact on human health. The average energy cost of the optimal energy mix goes up to 8.22 c€/kWh.

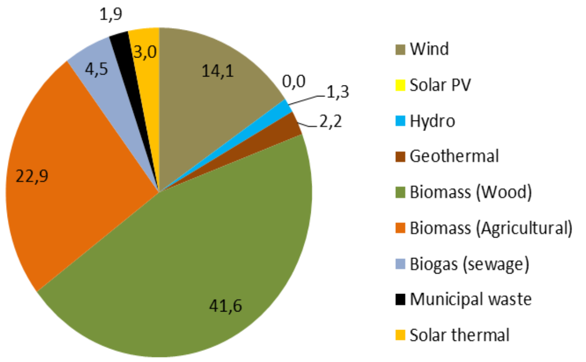

Figure 2: Optimal national portfolio of renewable energy sources with respect to economic, human health, environmental and climate impacts

The resulting portfolios are in line with the ideal energy mixes derived from other models in many regards; however, it is the strength of the approach discussed in our paper that it provides a smoother transition between the solutions than a model based on a LP problem where an appropriate alternative is generally used to the extent possible, limited by the potential or other constraints. At low number of constraints, no realistic results can be obtained from these types of solutions. It is another important feature of our model that it can deal with the level of saturation in the market; our approach is based on applying a linear increase in price as a function of installed capacity. For an exact description of the problem, it would be necessary to identify a more accurate relation between the level of saturation of the available potential and the costs that requires further analysis of each alternative. However, as it is difficult to have access to the economic data of most investment projects due to confidentiality issues, a statistical approach [15] seems to be problematic in this regard.

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