POWER GENERATION PORTFOLIO OPTIMIZATION BY EXTERNALITY MINIMIZATION

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ABSTRACT

Electricity generation is responsible to a large extent for the climate change all over the world. To reach the sustainable power supply the RENewable ratio should be raised and the CO_2 *emission technologies should be rolled back. The indirect cost of the climate changes appearing later, the harmful effects and the irreversible environment change are expressed by the externality cost. Hungary undertook the raise of the REN ratio to 13% for year 2020. There are many scenarios showing the way how to reach the (very optimistic) targets. This paper shows a linear programming optimization technique how one can define the optimal portfolio having clear data and targets. The key of the problem is to find approved initial data and objectives accepted by the society that we want to reach. In practice there are dozens of real and lobby tasks, so it is really hard to judge what is the multi-compound-objective function what we optimize for.*

Keywords**:** *power plant portfolio, externality minimization, Single Objective Optimization, renewable sources*

1. OBJECTIVES

The European Union defined national quotes for the ratio of the renewable energy generation. For Hungary this share is 13% of the total generation for the year 2020. The current share is only 4% that is why new sources must be set up. Each technology has special requirements, effects so it is not easy to say which type must be developed, how the new renewable level should be fulfilled. The Hungarian Energy Authority started a process for the definition of the new generating capacities based on the following criteria:

- definition of the cheapest generation portfolio
- definition of the lowest CO_2 emission portfolio
- definition of the lowest external cost portfolio

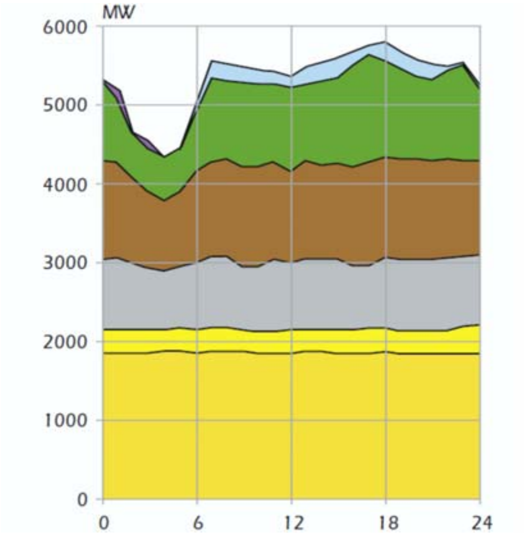


Fig. 1 Daily generation portfolio (source: MAVIR)

The cheapest means that it requires the least financial effort at present but the environmental pollution is not taken into the consideration. The CO_2 emission (and other climate changing emissions) can be measured in a relatively exact way. The notion of the external cost is given below.

Externality means an external economic impact that is not taken into consideration in the present transaction. E.g. now we produce cheap electricity, but no one calculates the huge future costs of the nuclear waste bury or the costs of the CO_2 caused climate change. These costs must be paid by the future economy, by the future society. We talk about internalization of the externality if we assign these costs to the present transactions. In the price of the electricity over the fuel, maintenance and operation costs we should separate funds to avoid these harmful effects.

private cost + external cost = social cost

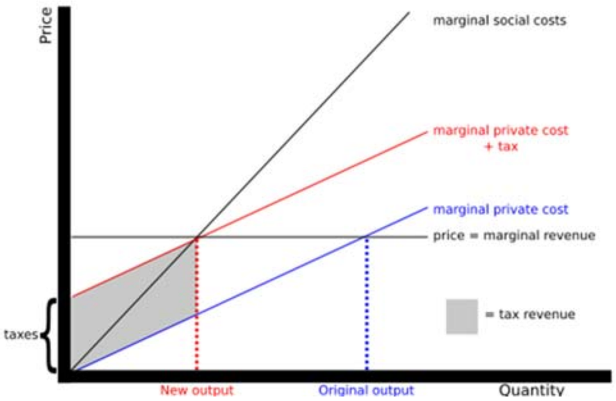


Fig. 2 The difference between the private and society costs [1]

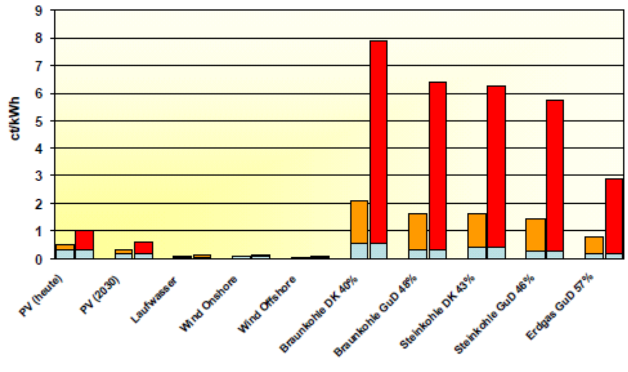


Fig. 3 External cost values (source: BMU, 2007)

The external cost calculation can deal with the green house gas emission, natural resource and area usage, health damage and landscape changes, too. It is a really complex process but several projects dealt with it already

- EU ExternE project
- NEEDS consortia (New Energy Externalities Development for Sustainability)
- USA NSA project „Hidden Cost of Energy" project
- German BMU project „Externe Kosten der Stromerzeugung" project, etc.

We used the following data in our calculations.

Table 1 External costs we used in the calculation

TECHNOLOGY		CO_2 emission g/kWh	External cost c€/kWh
1	**Hydro**	15 (10-20)	0,2 – 0,45
2	**Wind**	25 (10-40)	0,1 – 0,3
3	**Biomass**	1000 (550-1000)	0,1 – 1,0
4	**Biogas**	„0" (800)	
5	**Waste incineration**	1000 (400-1000)	
6	**PV**	130 (50-200)	0,1 – 0,6
7	**Solar thermal**	170 (170-200)	
8	**Autonomous (Wind+PV)**	78 (75-120)	
9	**Heat pump**	40-215	
10	**Geothermal**	86	
11	**Green hydrogen**	80	
12	**Coal**	1100 (660-1200)	1,5 – 4,5
13	**Natural gas**	520 (370-580)	0,4 – 2,5
14	**Nuclear**	10 (5-15)	0,007 – 1,0

2. OPTIMIZATION

In simple cases we seek for Single Objective Optimum (SOO), in other cases we optimize by many aspects (Multi Objective Optimization – MOO). The energy strategy, the definition of the future energy mix is a MOO problem. Nowadays there is a large variety of numerical optimization tools. Further on we demonstrate that the above mentioned data are appropriate for the investigation of the future alternatives. In the demonstration we use SOO.

Table 2 Objectives

CO_2	CO_2 emission minimization
EXT	External cost minimization
INV	Investment cost minimization

These calculations demonstrate that the rough SOO produces really distinct scenarios so it is not recommendable to use only the cheapest OR smallest emission version.

The fixed data:

- existing power generation capacities
- enlarging possibilities
- yearly energy demand (today 40 TWh and 50 TWh in 2020)
- load factor
- maximum energy production
- minimal energy production
- external cost/MWh
- CO_2 emission/MWh
- investment cost
- lifetime

Table 3 Power source data

Renewable	***type***	***mx. built in cap.***	***max. load factor***	***energy potential***	***energy produced/built in MW***	***external cost)***	***CO_2 emission***
		MW		**TWh**	**TWh/MW**	**MEUR/TWh**	**Mt/TWh**
	nuclear	3500	0,95	29,1	0,008322	2	0,015
	coal	1500	0,75	9,9	0,00657	53	0,8
	CCGT gas	4500	0,8	31,5	0,007008	23	0,5
R	**hydro**	500	0,5	2,2	0,00438	2	0,015
R	**wind**	1500	0,2	2,6	0,001752	1	0,025
R	**biomass (central)**	500	0,5	2,2	0,00438	33	0,4
R	**PV**	200	0,15	0,3	0,001314	2,5	0,13
R	**geothermal**	100	0,5	0,4	0,00438	3	0,086
R	**biogas**	250	0,6	1,3	0,005256	3	0
	total			**79,5**			

The potential development ranges:

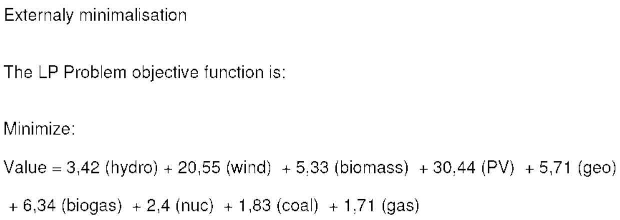
Table 4 Power plant development ranges

type	***present capacities (MW)***	***potential enlargement in 10 years (MW)***
nuclear	2000	1500
coal	1100	400
CCGT gas	3500	1000
hydro	50	450
wind	300	1200
biomass (centralized)	300	200
PV	1	199
geothermal	5	95
biogas	50	200
total	**7306**	**5244**

The following SOOs was done:

- CO_2 emission minimization
- CO_2 emission minimization, 13% renewable
- Externality minimization
- Externality minimization, 13% renewable
- Investment minimization
- Investment minimization, 13% renewable

All the cases take into account the present existing portfolio. In the following lists the externality minimization process using the Archer's Linear Programming Tool can be seen. First we define an objective function to minimize. This is the total external cost coming from the individual externality of each generation type.



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Externaly minimalisation

The LP Problem objective function is:

Minimize:

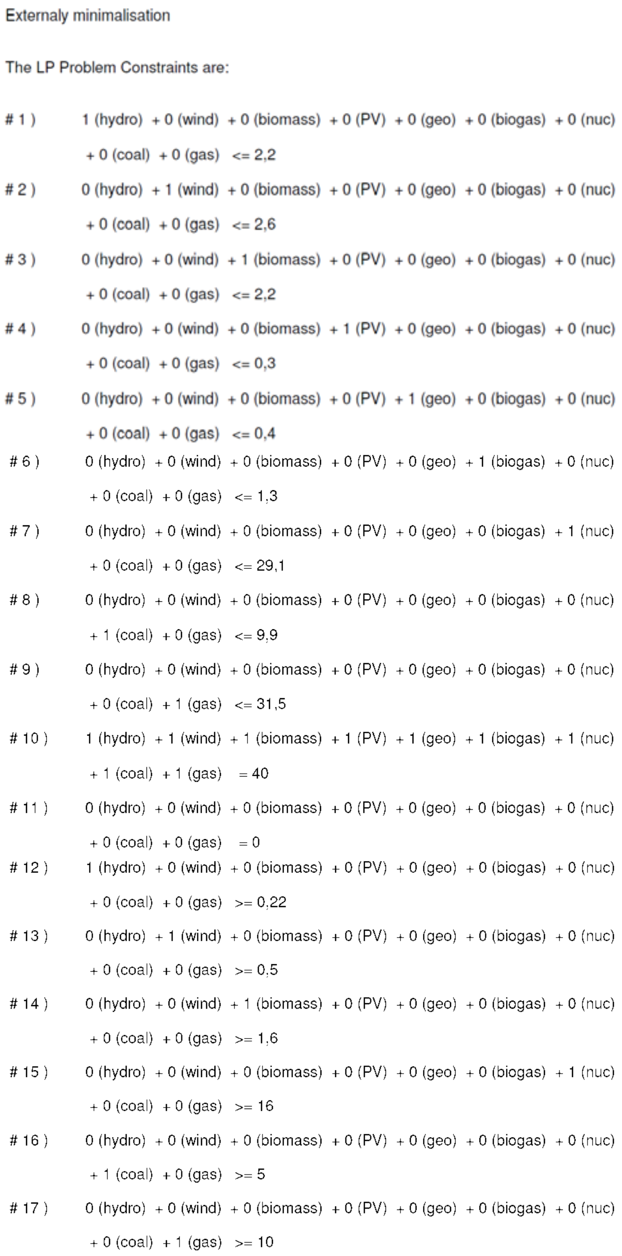
Value = 3,42 (hydro) + 20,55 (wind)  + 5,33 (biomass)  + 30,44 (PV)  + 5,71 (geo)

 + 6,34 (biogas)  + 2,4 (nuc)  + 1,83 (coal)  + 1,71 (gas)
```

Fig. 4 Objective function of the externality minimization

The second step is to set up the different constraints as the existing minimum capacities, the possible extension ranges. After having a solution that minimizes our objective function we can calculate e.g. the total CO_2 load, total investment cost necessary, total operation costs. By setting up different constraint sets different alternative development scenarios can be obtained.

The following table shows the result portfolio of the externality minimization. The total generated energy is 50 TWh, the renewable ratio is 13%. The total external cost is 401 MEUR. Coal and biomass firing is stopped. The CO_2 emission is 7,8 Mt per year. It is almost the half of the present emission.



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Externaly minimalisation

The LP Problem Constraints are:

# 1 )     1 (hydro)  + 0 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 0 (coal)  + 0 (gas)   <= 2,2
# 2 )     0 (hydro)  + 1 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 0 (coal)  + 0 (gas)   <= 2,6
# 3 )     0 (hydro)  + 0 (wind)  + 1 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 0 (coal)  + 0 (gas)   <= 2,2
# 4 )     0 (hydro)  + 0 (wind)  + 0 (biomass)  + 1 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 0 (coal)  + 0 (gas)   <= 0,3
# 5 )     0 (hydro)  + 0 (wind)  + 0 (biomass)  + 0 (PV)  + 1 (geo)  + 0 (biogas)  + 0 (nuc)
          + 0 (coal)  + 0 (gas)   <= 0,4
# 6 )     0 (hydro)  + 0 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 1 (biogas)  + 0 (nuc)
          + 0 (coal)  + 0 (gas)   <= 1,3
# 7 )     0 (hydro)  + 0 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 1 (nuc)
          + 0 (coal)  + 0 (gas)   <= 29,1
# 8 )     0 (hydro)  + 0 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 1 (coal)  + 0 (gas)   <= 9,9
# 9 )     0 (hydro)  + 0 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 0 (coal)  + 1 (gas)   <= 31,5
# 10 )    1 (hydro)  + 1 (wind)  + 1 (biomass)  + 1 (PV)  + 1 (geo)  + 1 (biogas)  + 1 (nuc)
          + 1 (coal)  + 1 (gas)    = 40
# 11 )    0 (hydro)  + 0 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 0 (coal)  + 0 (gas)    = 0
# 12 )    1 (hydro)  + 0 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 0 (coal)  + 0 (gas)   >= 0,22
# 13 )    0 (hydro)  + 1 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 0 (coal)  + 0 (gas)   >= 0,5
# 14 )    0 (hydro)  + 0 (wind)  + 1 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 0 (coal)  + 0 (gas)   >= 1,6
# 15 )    0 (hydro)  + 0 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 1 (nuc)
          + 0 (coal)  + 0 (gas)   >= 16
# 16 )    0 (hydro)  + 0 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 1 (coal)  + 0 (gas)   >= 5
# 17 )    0 (hydro)  + 0 (wind)  + 0 (biomass)  + 0 (PV)  + 0 (geo)  + 0 (biogas)  + 0 (nuc)
          + 0 (coal)  + 1 (gas)   >= 10
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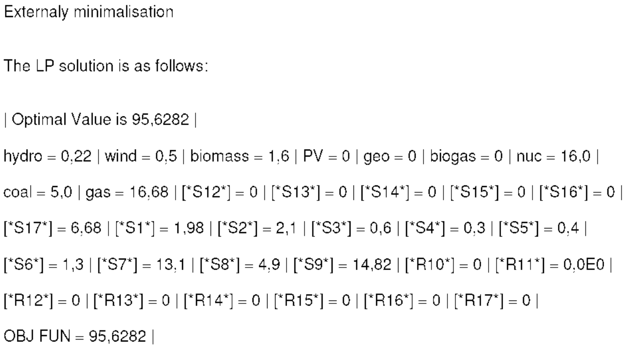
Fig. 5 The externality min SOO constraint table



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Externaly minimalisation

The LP solution is as follows:

| Optimal Value is 95,6282 |

hydro = 0,22 | wind = 0,5 | biomass = 1,6 | PV = 0 | geo = 0 | biogas = 0 | nuc = 16,0 |

coal = 5,0 | gas = 16,68 | [*S12*] = 0 | [*S13*] = 0 | [*S14*] = 0 | [*S15*] = 0 | [*S16*] = 0 |

[*S17*] = 6,68 | [*S1*] = 1,98 | [*S2*] = 2,1 | [*S3*] = 0,6 | [*S4*] = 0,3 | [*S5*] = 0,4 |

[*S6*] = 1,3 | [*S7*] = 13,1 | [*S8*] = 4,9 | [*S9*] = 14,82 | [*R10*] = 0 | [*R11*] = 0,0E0 |

[*R12*] = 0 | [*R13*] = 0 | [*R14*] = 0 | [*R15*] = 0 | [*R16*] = 0 | [*R17*] = 0 |

OBJ FUN = 95,6282 |
```

Fig. 6 The externality min SOO solution

Table 5 Power source data

hydro	2,2	TWh
wind	2,6	TWh
biomass	0	TWh
PV	0,3	TWh
geo	0,4	TWh
biogas	1	TWh
nuc	29,1	TWh
coal	0	TWh
gas	14,4	TWh
EXT cost	401,35	MEUR

3. THE RESULTS

- This methodology is appropriate for the qualitative strategy definition
- The energy portfolio definition is a real MOO problem
- Instead of the politicians the numerical solution provides a good sustainable solution
- The future portfolio is not really sensitive to the amount of energy produced
- It is forbidden to build up an energetic monoculture
- In the current low cost solution the future operation costs are enormous
- The power plant building and operation and externality costs are in the same range

The data are only for information!

Table 6 The power generation portfolio development alternatives

	CO_2 emission minimization	CO_2 emission minimization	EXT cost minimization	EXT cost minimization	INV. cost minimization	INV cost minimization	INV cost minimization	
Total energy	50	50	50	50	40	50	50	TWh
hydro	2,2	2,2	2,2	2,2	0,22	0,22	2,2	TWh
wind	2,6	2,6	2,6	2,6	0,5	0,5	0,5	TWh
biomass	2,2	0	0	0	1,6	1,6	2,2	TWh
PV	0,3	0	0,3	0,3	0	0	0	TWh
geo	0,4	0,4	0,4	0,4	0	0	0,4	TWh
biogas	1,3	1,3	1,3	1	0	0	1,2	TWh
nuc	29,1	29,1	29,1	29,1	16	16	16	TWh
coal	0	0	0	0	5	7	7	TWh
gas	11,9	14,4	14,1	14,4	16,68	24,68	20,5	TWh
REN	18 %	13 %	13,6 %	13 %	5,8 %	4,64 %	13 %	%
CO_2	7,4379	7,7689	7,65	7,8	13,23,	18,83	17,05	Mt
External cost	**417,35**	**401,5**	**395,35**	**401,35**	**733,94**	**1023,94**	**952,4**	MEUR
Yearly power plant building cost	**182,52**	**165,94**	**174,56**	**173,17**	**95,62**	**112,96**	**125,70**	MEUR
Yearly power plant operation costs	**1304**	**1403**	**1383**	**1401**	**1540**	**2128**	**1882**	MEUR

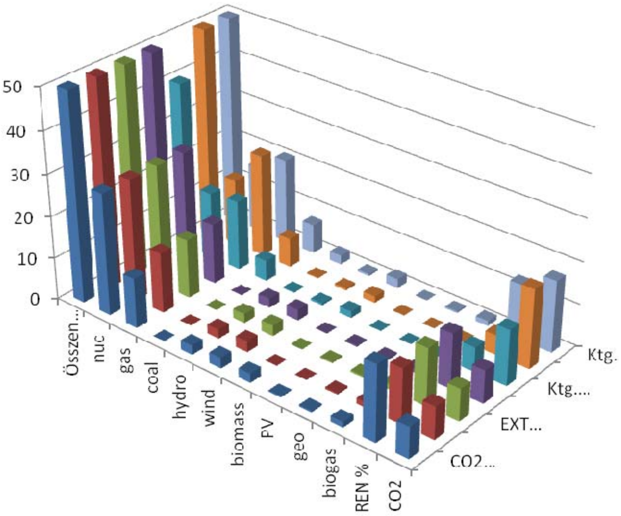

Fig. 7 Generation ratios in different optimization alternatives (data of table 6)

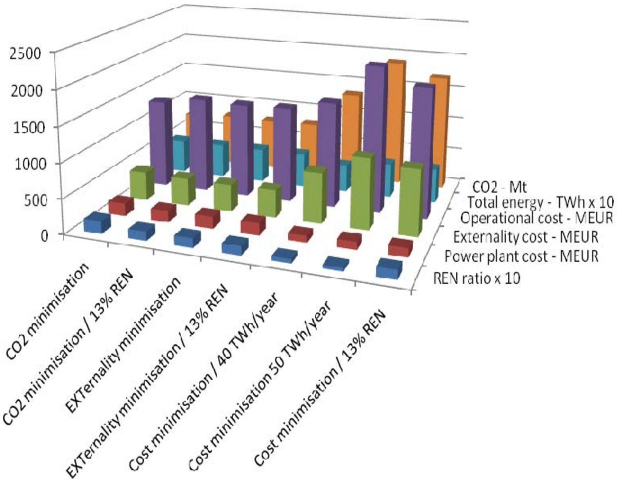

Fig. 8 Yearly costs of the alternatives (MEUR) (data of table 6)

4. CONCLUSION

- The CO_2 minimum and external cost minimization produces recommendable scenarios
- The simple cost minimization implies huge CO_2 emission
- The gas heated part is cheap but is CO_2 producer
- The wind generation is welcome
- All the portfolios contain hydro generation
- The bulk central biomass firing is not the part of optimal mix
- All the alternatives contain nuclear generation (do not forget that any other pumped storage plant raises the external costs)

More detailed optimization with exact input data provides real results. We recommend this method for the national planning level.

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BIOGRAPHY

Peter Kádár, was born in 1963 in Budapest. He received his M.Sc. in 1987; PhD. in 1994 at the Technical University of Budapest. His preferred topics are the expert system applications, simulation of the power systems and renewable energy sources. He worked for the Power Station and Network Engineering Company; Research Inst. for Measurement and Computing Techniques till 1996. In the next five years period he was the managing director of DYNAdata Ltd. After being the associate professor at the Technical University of Budapest, recently he is an associated professor at Óbuda University, Department of Power Systems. He works as independent consultant of the Power Consult Ltd. too. He is member of the Hungarian Electrotechnical Association, the Neumann Janos Computer Science Association and CIGRÉ. He is the vice chair of IEEE Hungary section.