Exergy potential maps

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Abstract

Regional designers wrestle with specialist knowledge about the possibilities of transporting en converting existing unused, but substantial energy resources. Their language is making maps of possible futures, not formulas. This article is an attempt to bridge that gap and to raise critics from specialists to improve starting-points for regional design.

Keywords: Exergy, maps, regional planning, heat transport, the Netherlands

Introduction

As we learn from two laws of thermodynamics, energy can not be destroyed, but it is degraded by any conversion. Natural gas burning at a temperature of 1500°C is usually converted to hot water for heating buildings into a temperature of 20°C, without intermediate use. If we could link uses of work or intermediate temperatures (e.g. cooking) in-between, we could use the same energy more times in a cascade of functions. The extraction of useful energy in each stage of a range of conversions is called exergy.
And exergy can be destroyed or maximised.

1 Exergy

Usually, the term 'exergy' concerns the amount of work (W) extracted from a temperature difference ΔT.
Fig. 1 shows the maximally extractable amount of W related to ΔT. To extract work out of heat, an acceptable efficiency is reached beyond ΔT of 1000°C. However, smaller differences may be useful for intermediate heating, before the energy is completely degraded into lost exergy ('anergy'). So, in these cases the term exergy is also used for other intermediate applications than work. The exergy curve of useful heat will be steeper than the exergy curve of work in *Fig. 1*. But, how steep?

The maximum amount of heat from a high temperature source, useful as close to the original temperature as possible is dependent on the temperature difference and the investments between supply and demand (a function of their distance).

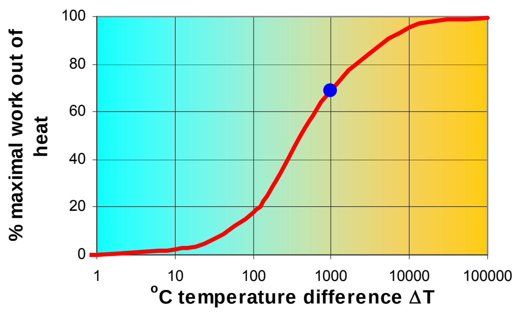


Fig. 1 Exergy of work[2]

The quantity and location of energy supply and demand was studied in the Dutch province of Groningen[3] and in the city of Almere[4], both reported in the second section below.
Now, the temperature requires a more detailed inquiry of the actual and possible applications per temperature class. For example, if an amount of heat at a temperature of 1500°C is available, could we find an application of that energy at 1400°C and settle it in the neigbourhood? How is the feasibility related to distance? Could we draw a reliable second curve in *Fig. 1*? What about the costs of transport, earlier a bottleneck of application (e.g. a Rotterdam case discussed below)?
These questions are not yet solved here, but elaborated in the third section for further investigation and open for suggestions.

2 Potentials mapped

The province of Groningen

Fig. 2, shows a map of potentials for electricity generation in the province of Groningen as a part of a study for the new provincial development plan. It shows the best location for wind parks, a tidal plant and a few 'blue energy' plants along the coast, a biomass-based industrial cluster in the centre, and for a new type of plant:: an inundation plant for occasional flooding of the deepest polders in case of emergency. Furthermore, there are small decentralised bio-digestion installations with combined heat and power (CHP) generation, spread through the country-side containing many isolated farms and villages. Energy values of solar radiation showed little variance over the province. The use of photovoltaic panels and small wind turbines. is possible anywhere support ing local self-supply. For large-scale solar plants, the energy properties of a northern place as Groningen are unfavourable.

Fig. 3 is the overlay map of heat and cold potentials. The map depicts the potentials of geothermal heat from aquifers at 3000 meters of depth, to be deployed through empty gas fields, shown as grey grids. The drill-holes of gas extraction are indicated by small blue triangles. The small dotted areas depict reasonable to good potential for heat and cold storage in shallow aquifers (30 tot 150 meters deep). Hollow circles are heat (outer red) and cold (inner blue) demand within the municipalities, whereas full circles pinpoint major sites of excess of heat or cold, which can be considered as sources of supply.

The excess of heat in industrial areas is evident. Nevertheless, the largest producer of heat, the Eems harbour area, now has no heat-demanding function close to it, so all heat is emitted into the air and sea. This can be altered by spatial planning taking these heat potentials into account.

Solar heat, again, is available anywhere and should be seized when possible. This also applies to local exchange of heat and cold with exhaust air, the soil and open water.

In regards to CO_2 capture, a four-steps strategy may be (1) avoid emission of CO_2 by energy-saving and sustainable energy sources, (2) use CO_2 in industrial and horticultural processes, (3) compensate for CO_2 emissions by CO_2 absorbers, and finally (4) storing CO_2 underground. This last option is possible in emptying gas fields that are not watered out after abandonment.

Fig. 4 summarises the last three options for the province of Groningen. The gas drill-holes are shown again.

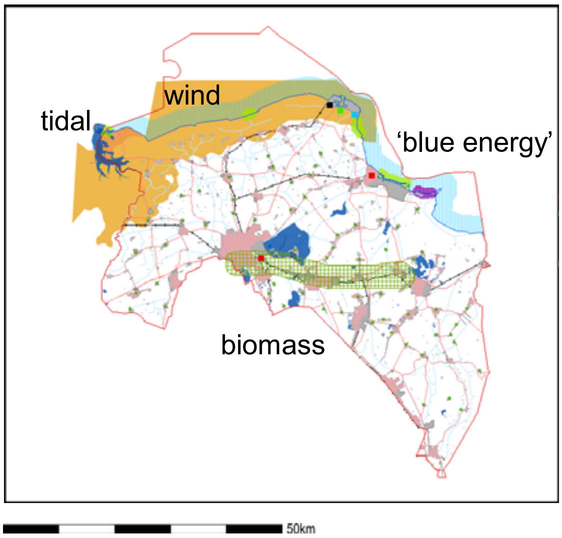


Fig. 2 Potentials for electricity generation

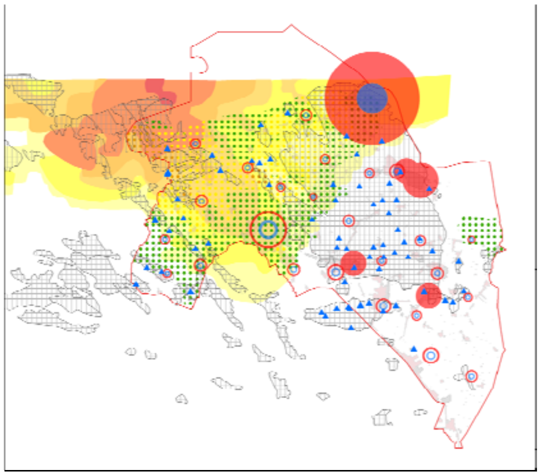


Fig. 3 Potentials for provision of heat and cold

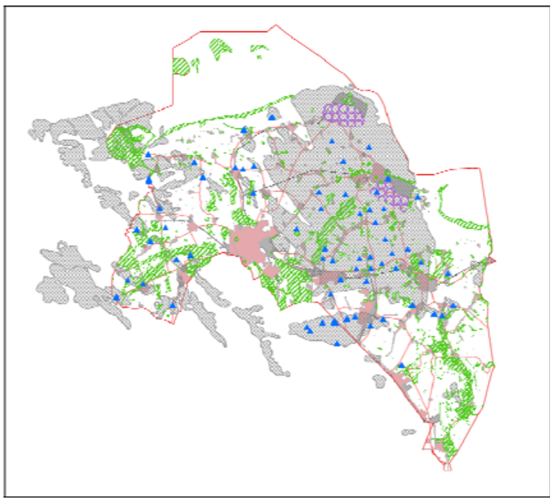


Fig. 4 Potentials for CO_2 emission mitigation: use in greenhouses, compensation by plants and storage in emptied gas fields

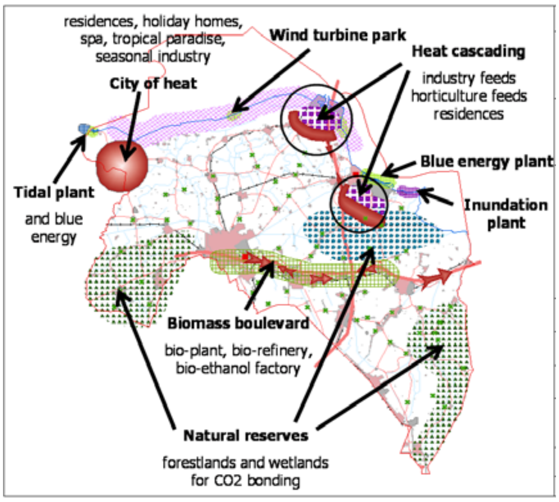


Fig. 5 Proposed spatial interventions

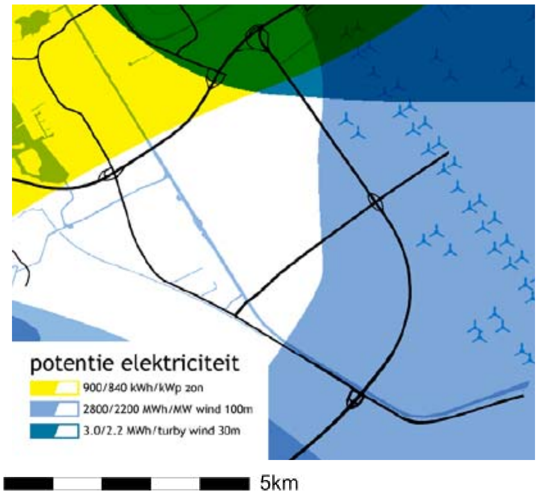


Fig. 6 Potential map for provision of electricity, depicting solar energy and wind power

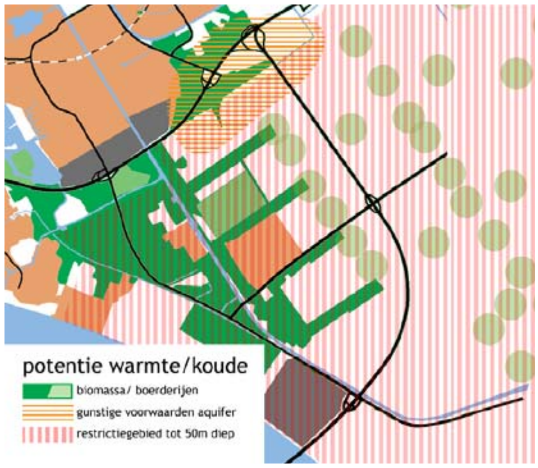


Fig. 7 Potential map for heat and cold, depicting biomass and farms, favourable conditions for open storage of heat and cold and the area of restrictions for this

Fig. 5 finally represents the interventions proposed on the basis of energy potentials. These proposals involved a wind park, a tidal plant, blue energy (osmosis) plants, an inundation plant, a cluster of biomass-related industrial activities, heat cascading solutions by housing developments and horticulture next to industry, and wet biotopes for CO_2 bonding.

The city of Almere

For the smaller scale case of a district development plan, similar energy potential maps were drawn for Almere, the Netherlands (*Fig. 6* and *Fig. 7*).

The measures proposed for the north side of Almere East in *Fig. 8* encompasses intensive developments alongside the A6 motorway with industry and housing, exchanging heat and cold (possibly with extension of the heat network from Almere-City) and using open storage of heat and cold in aquifers.

The approach for this dense area can be described as heteronomous[5].

Autonomous clusters are proposed around farms in the open agricultural area of Almere East: low-temperature heating dwellings with greenhouses, bio-fermentation with CHP, small wind turbines and PV. Alongside the A27 motorway, large windmills will provide additional sustainable power and reed fields will purify water of the area.

Fig. 9 shows another option: only the western part of the A27 motorway is developed, with highly intensive housing against the A27 ('noise wall') with a centralised energy infrastructure, and less intensive developments towards the west (of which only one variant is shown).

Fig. 8 Plan A for Almere East

Fig. 9 Plan B

These proposals are currently taken into account for the elaboration of this new district. An energy potential study of the entire Almere region is ongoing, and new studies are expected for other areas of development.

3 Supply and demand

The example of Rotterdam

For more than 20 years plans have been made to use the superfluous heat of industries near Rotterdam (available at 100°C) for heating dwellings or glasshouses, for example at a distance of 18 km. The supply would be enough to heat 500,000 houses. This never succeeded because it would take 20 years to repay the investments by the profits and contracts. Such a long period was not acceptable for the suppliers and the users.

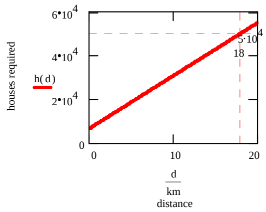
However, the advantages to use sources of superfluous power are not only a potential reduction of energy costs in the long term, but also a reduction of environmental pressure by heat (particularly on aquatic ecosystems), CO_2 and NO_2. Because of the NO_x pressure in the region the former plans became actual and gained political involvement. A recent plan connecting 50,000 houses calculated savings in terms of emission rights at €25 million for a total investment of approximately €125 million (€7 million/km or €2500/dwelling).[6]

Investments like this have to be made because sources and use differ in space, time and quality. That raises questions of transport, storage and minimisation of exergy losses as discussed below.

Space

Supply and demand differ in space.
High quality energy is easier to transport than heat. If heat transport requires:
€ i_b basic investments, € i_d investments per km, d km heat transport and i_y interest during y years, then the total investment required is $i = (i_b+i_d \cdot d) \cdot (1+i_y)^y$.

If € i_h investment per house, paid in y years, is acceptable for contracts for such a period, the required number of served houses 'h' should increase by distance 'd' until $h(d)=i / i_h$ to meet the required total investment (see Fig. 10).



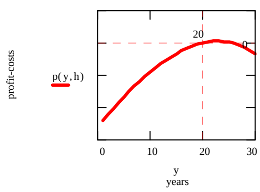


Fig. 10 Houses (distance) Fig. 11 Profit (years)

If the profit per dwelling per year equals € p_y, then i_h should be at most $p_y \cdot y$. If $i_h = p_y \cdot y$, then the sum $i_h \cdot h - i$ often reaches a maximum near $y \approx 20$ years because after such a period the increasing interest in i surpasses $i_h \cdot h$ (see Fig. 11). The energy need of 1 ha of greenhouses is comparable to the need of 250 dwellings.

Time

Supply and demand differ in time. So, transport investments may involve costs of storage.
Fig. 12 shows some alternatives made comparable for the highest quality of energy. The tentative maximum efficiencies for storage and retrieval mentioned are different for heat.

	Storage	Efficiency		Surface required for 1 GW_e	
	gross	(max.)	net	24 hours	0.5 year
	Wa^7/m^3	%	Wa/m^3	$x1km^2 \cdot 1m$ = 1million m^3	
Potential energy					
water (fall, 1 m)	0.0003	30%	0.00009	29374	5360781
water (fall, 10 m)	0.003	75%	0.002	1370	250000
water (fall, 100 m)	0.03	90%	0.03	91	16667
50 atm. pressed air	1.3	50%	0.6	5	833
Kinetic energy					
fly weel	32	85%	26.9	0.10	19
Chemical energy					
natural gas	1	80%	0.8	3.42	625
lead battery	8	80%	6.3	0.43	79
hydrogen (liquid)	274	40%	109.5	0.03	5
petrol	1109	40%	443.6	0.01	1
Heat					
water (70°C)	6	40%	2.5	1.10	200
rock (500°C)	32	40%	12.7	0.22	39
rock salts (850°C)	95	40%	38	0.07	13

Fig. 12 Storage capacity (for conversion into electricity) of some systems[2]

Fig. 12 indicates chemical storage as the best and using water levels as the worst if there is not much space.
However, dropping 1 $km^2 \cdot 1$ m (a million m^3) of water 1 m by gravity delivers 9807 MJ or 311 Wa, which is, regained with an efficiency of 30% during a day roughly $34kW_e$.

Tides do so twice a day both in and out, gulfs several times a minute.
In Groningen (see *Fig. 2*) the tide is 2.4 m, which can be stored in the Lauwersmeer basin of 36 km^2. If 36 km^2·2.4 m water is raised and dropped 2.4 m twice a day, a tidal plant with an efficiency of 30% and large investments can deliver 14 MW (the average power of 18 wind turbines of 2 MW_{peak}).
Heat used as heat has much better efficiencies than shown in *Fig. 12*. So, if the investments meet the profit, then it is a realistic option.
The rather efficient fly wheels may be interesting if they are visible for a community to see how much energy is still in stock.

Quality

The difference in energy quality mainly concerns the temperature difference between supply and demand. After an inventory of these differences and their exact locations a quest starts for intermediate uses between the greatest differences, for example burning at 1500°C and heating at 20°C. However, there are not many substantial applications in-between. A temperature table of industrial applications would be useful, but still unknown by the authors. A table of industrial materials, their auto-ignition temperature, flash point, flame temperature, melting point, boiling point and other characteristics would be a good starting-point for innovative ideas.
The heat surplus of cogeneration devices, for example in greenhouse complexes, offer some opportunities. A recent report[8] considers the delivery of 80°C heat from 800 ha of greenhouses for 2800 dwellings at 3 km feasible. However, cogeneration does not fit in a cascade starting with a substantial supply at 1500°C. The question is if space heating will remain the main problem. If thermal insulation of buildings is the first priority, cooling becomes the main problem to overcome, aggravated by climate change. And cooling is primarily required when the sun shines. Heat pumps driven by solar energy could solve that problem. The gained heat can be stored for the cold season by the same system.

Conclusion

An inventory of locally available sustainable energy sources and the translation of these into energy potential maps is an important first step to design a more energy-effective regional or urban plan. The proposed interventions resulting from this need to be energetically and financially calculated to better determine the significance and feasibility of the proposal.
In the near future, the concept of exergy, the quality part of energy, will play an essential role in spatial planning when searching for an optimal tuning of supply and demand of waste heat. The difference in space, time and energy quality needs to be solved, requiring spatial and technical measures. A financial estimate of the consequences of these will define the feasibility. It should be acknowledged that apart from the saved primary energy, heat cascading will also avoid pollution of CO_2, NO_x and waste heat into the environment, implicitly accepted in the current energy system.
Further research is needed, but ongoing projects such as SREX[9] will hopefully solve many riddles still present in this interesting and valuable area of applied science.

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