Old New Territory
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ENERGY

Heating and cooling energy, as well as electricity for the Frankfurt Bridges, will be provided by near-surface geothermal energy, waste heat from data centers, and photovoltaic (PV) and hybrid (PVT) solar panels.

Frankfurt's bridges, as well as the parking lots and roofs of buildings along the bridges, support the generation of over 415 GWh of electricity and the generation and recovery of nearly 440 GWh of thermal energy per year. Of this, the bridges only consume about 140 GWh/a of electricity and 40 GWh/a of thermal energy themselves; they can provide the rest to the city.

The bridges thus offer the opportunity to implement the urban energy transition in the middle of the city, initially in the bridge district on a second level, from where it can then slowly spread to the city.

Accordingly, it makes sense for the bridge company to hand over the bridge corpus, including its lines, to the Frankfurt public utility company after completion of the construction work in order to ensure that it is interlinked with the municipal infrastructure.

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THE URBAN ENERGY TRANSITION

Pulling out all the innovation stops for renewables – and transferable to the existing stock

CURRENT DEMAND OF THE BRIDGES

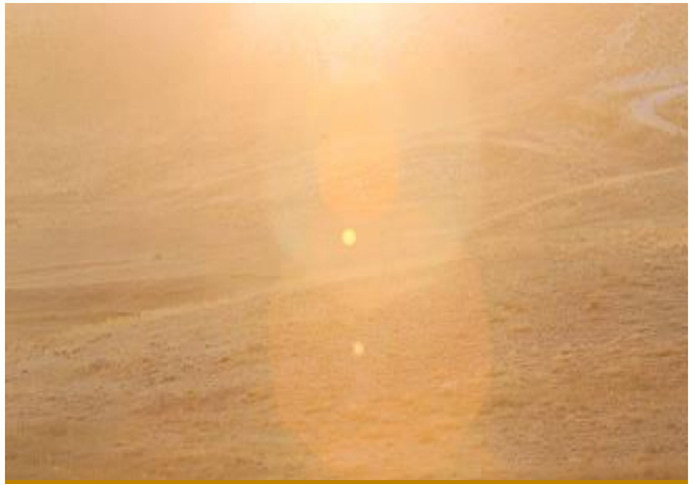
Economical consumption with a luxurious lifestyle: operating the right levers

HEATING AND COOLING REQUIREMENTS OF THE BRIDGES

Achieving maximum comfort with a minimum of energy – through technology, control and building physics

PHOTOVOLTAICS AS DISTRICT POWER

Large amounts of electricity are generated with invisible or aesthetically beautiful photovoltaics



HEAT GENERATION AND GEOTHERMAL STORAGE

Solar heat and waste heat from data centers or industrial parks are stored underground in summer

THE ENERGY INFRASTRUCTURE OF THE FUTURE

The interaction of centralized and decentralized energy generation can be optimized by a storage landscape

The Urban Energy Revolution

Old New Territory Frankfurt

The urban energy turnaround can be realized on Frankfurt's bridges

From photovoltaics to solar thermal in hybrid collectors and waste heat from data centers to geothermal energy - the city's complete renewable energy potential can be harnessed and optimally balanced: not only for the Frankfurt bridges themselves, but also for buildings, greenhouses and road infrastructure, as well as hydrogen and electricity-powered vehicles along the bridges. Photovoltaics for electricity generation and solar thermal energy for heating are key principles in the energy reorganization of the city of Frankfurt. The integration of energy generation and storage in the middle of a city's existing structure is possible with the bridge network.

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Content: The energy transition in Frankfurt – starting position and goals

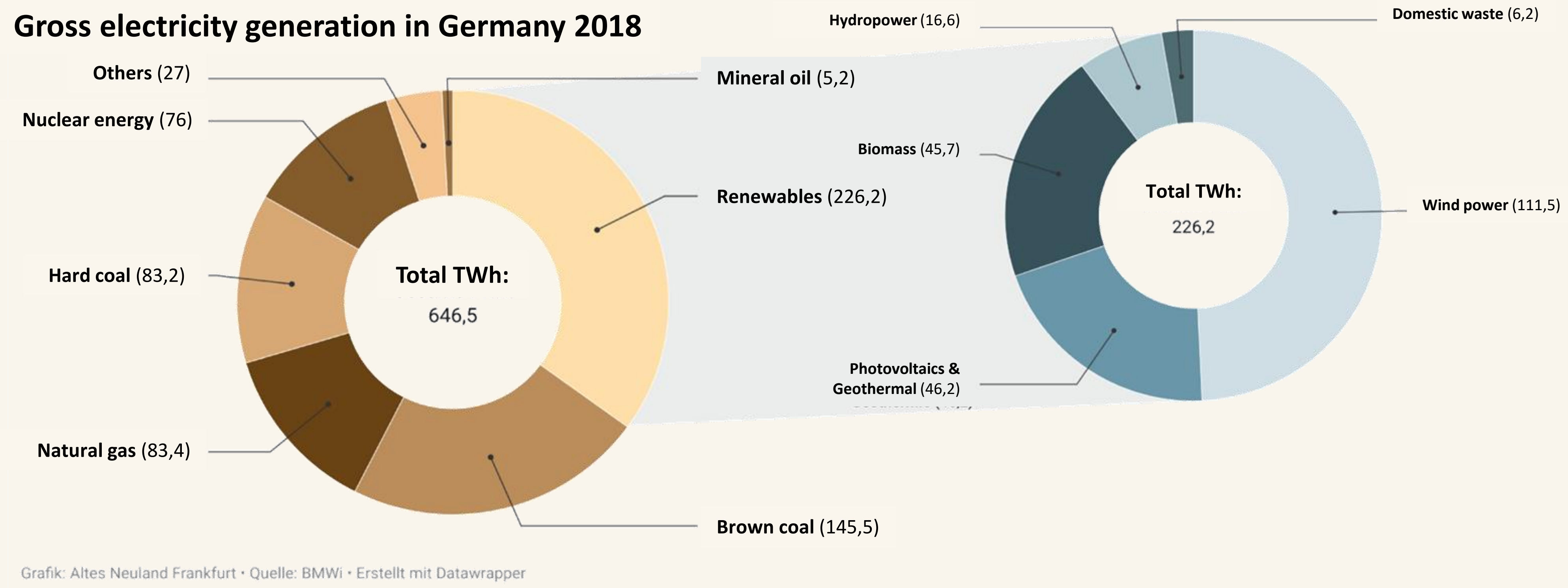
The share of renewable energies in total energy generation in Frankfurt is still extremely low.

However, Frankfurt has a large photovoltaic potential that should be exploited. On or along Frankfurt's bridges, this is happening to the fullest extent. Solar modules are used to generate electricity for the bridge itself and the neighboring districts. For such decentralized power generation and use, the bridges need so-called supply centers that control supply and consumption every few hundred meters and are also linked to each other.

Designed as hybrid collectors, the solar modules collect not only sunlight for the purpose of electricity generation, but also solar heat, which is consumed directly in winter and can be stored in the ground in summer for the next winter.

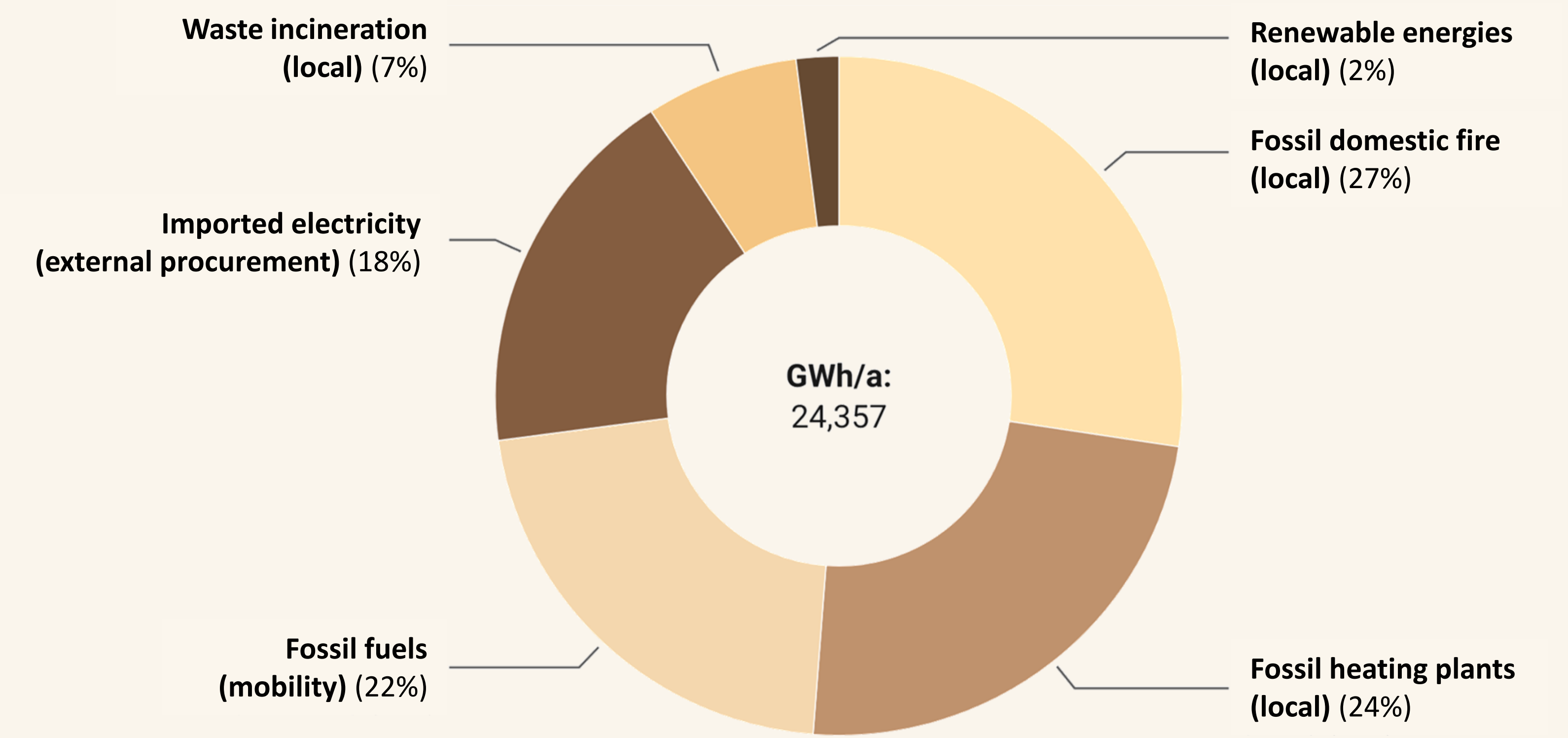
By 2050, Germany wants 100% electricity from renewable sources – because electricity generation is responsible for 40% of CO_2 emissions in Germany

Renewable energies already account for more than one-third of gross electricity generation.



In Frankfurt, renewable energies do not yet have a significant share in the total amount of energy generated

Frankfurt still has a long way to go from 2% renewable energy (as of 2019) to urban energy transition: combustion processes are used to generate electricity (waste and coal) and either district heating from them or fossil fuels such as gas and oil are used for heating.



Source: Municipal Profile Regional Association Frankfurt RhineMain 2019

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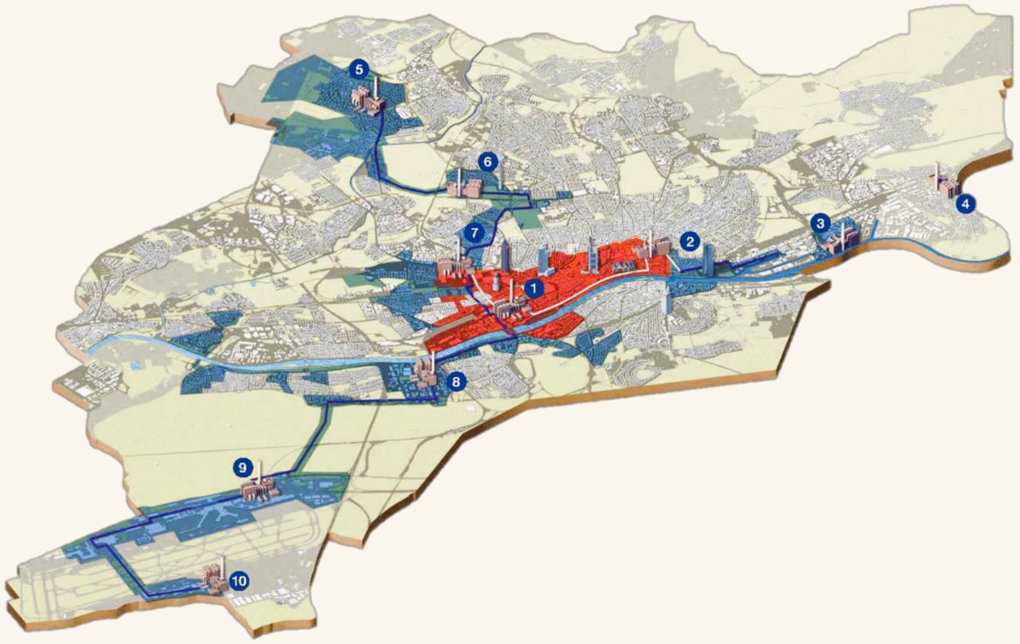
Frankfurt's power plants emit - as of 2019 - over 800,000 tons of CO2 p.a. through combustion



Although the amount of CO2 emitted has decreased since 2019 due to forward-looking measures, it is still in significant orders of magnitude.

Most power plants are fueled by coal and/or natural gas

1 HKW West
Electricity: 262 MW
Heat: 430 MW
Fuel: Coal & Natural Gas

2 HKW center
Power: 4 MW
Heat: 58 MW
Fuel: natural gas

3 HW Schielestraße
Heat: 19 MW
Fuel: natural gas

4 Biomass power plant Fechenheim
Power: 12 MW
Heat: 27 MW
Fuel: wood waste

5 HKW Northwest City
Power: 72.5 MW
Heat: 120 MW
Fuel: Household waste

6 HW Raimundstraße
Heat: 21 MW
Fuel: natural gas

7 HKW Fair
Power: 5.3 MW
Heat: 112 MW
Fuel: natural gas

8 HKW Niederrad
Power: 70 MW
Heat: 235 MW
Fuel: natural gas

9 Heating/cooling plant at the airport
Electricity: 262 MW
Heat: 430 MW
Fuel: natural gas

10 HW South
Heat: 15.4 MW
Fuel: natural gas

In Frankfurt, wind and solar energy account for only one-eighth of electricity generation - as of 2019

Frankfurt has the structural disadvantage that wind power cannot be expanded because of its proximity to the airport. In addition, the city's area is comparatively small, so no huge solar parks could be built on it without sacrificing green spaces or land needed for housing.

Accordingly, the focus for the generation of more sustainable electricity has so far been mainly on technological optimization with regard to the energetic use of waste and biomass.

Key figure	Unit	2019	2018	2017
Electricity generation by primary energy source				
Hard coal	MWh	263.545	344.844	525.390
Natural gas	MWh	879.196	617.809	1.035.787
Biomass	MWh	62.655	83.806	83.708
Waste	MWh	157.356	234.590	233.482
Wind	MWh	171.473	156.936	156.693
Sun	MWh	32.699	34.900	31.506
Total	MWh	1.566.923	1.472.886	2.066.566

Dams and wind turbines could not bring Frankfurt to urban energy transition, but electricity generation from photovoltaics is a viable solution for the city to meet 10% of Frankfurt's electricity needs, according to a study by Frankfurt University of Applied Science

A solar cadastre was developed by the Frankfurt University of Applied Science to determine the solar potential of all roof and open spaces in Frankfurt.

Every homeowner can therefore determine exactly what energy supply options are lying dormant on his or her roof.

More than 10% of Frankfurt's electricity needs could be met in this way. Over 400,000 tons of carbon dioxide could be saved per year - a considerable amount considering that Frankfurt currently still produces its electricity mainly by burning coal and natural gas.

However, aesthetic impact and installation expense are common reasons for homeowners not to use photovoltaics

For existing buildings, homeowners shy away from the expense of tampering with a functioning, tight roof or having to run new lines through rented space.

In addition, Mainova's power plants are all already there, "up and running", largely depreciated and thus relatively inexpensive suppliers of electricity. The central supply of energy simply has supplier advantages due to historical development.

And the most important knockout criterion for many building owners: photovoltaic systems usually do not change the appearance of a building in its favor, as they are classically developed primarily with efficiency in mind, not beauty.

The problem of aesthetics

No matter whether slate roof or roof with beautiful red tiles: The usual photovoltaic modules are generally not an optical gain for a building.

However, they are not optimized for aesthetics, but efficiency is clearly the main focus: Black is the best color for photovoltaics to absorb as much light as possible. And the eye-catching grid lines that crisscross the panels also have a purpose: they capture the generated electricity as closely as possible.

The industry has long recognized the aesthetics problem, and accordingly, there are now also colorful panels that are not crisscrossed by conspicuous metal grids.

The only drawback is that they are usually more inefficient than the conventional unsightly panels.

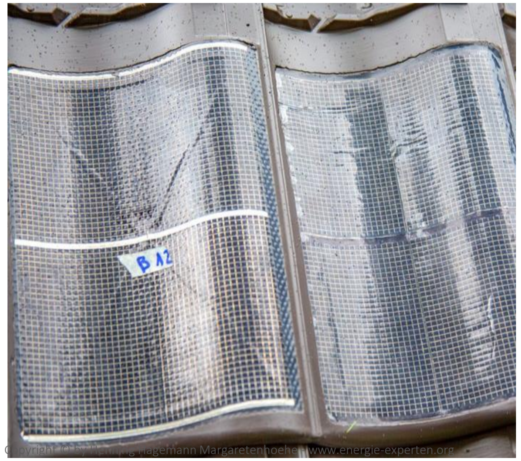
The motto for Frankfurt's bridges is therefore: better aesthetically pleasing or invisible photovoltaics with less efficiency than no photovoltaics at all with a lot of efficiency - at least in the inner city area. Efficiency-optimized photovoltaics, on the other hand, will be installed on the outer arms of the bridges, where they cannot disturb anyone.

Photovoltaic on the roof should look in the best case like the roof without photovoltaic

Even though many suppliers are working on it: There are still no roofs that have been covered with an authentic-looking red tile or a convincing photovoltaic slate imitation. Deceptively real looking imitations are not yet on the market. And the innovative products that have already been developed still have comparatively low efficiency.

Tesla has been working for years to develop roof tiles that actually look like red roof tiles or natural slate. But so far there are no realized projects on the market and no such roof tiles are available on the market as a mass product.

The Institute for Building Physics at the University of Stuttgart has developed roof tiles covered with photovoltaic cells that look different from close up than the black roof tiles of the historic buildings on Margarethenhöhe in Essen, but from a distance blend in unobtrusively with the roof structure.



Unfortunately, the costs per element are (still) relatively high because they are not (yet) mass products. It is simply not yet worthwhile for building owners to rely on beautiful but expensive aesthetic solutions with a low return on investment.

This is to change with the Frankfurt bridges: All "invisible" photovoltaic elements, which are already available in Europe and do not even look like photovoltaics, are to be used on the roofs of the bridges, as the bridges also serve as a "showcase of innovations" for this purpose. Accompanied by research institutes, regular evaluations aim to further optimize the products. And every visitor to the bridge gets an up-to-date overview of applied innovations, which are thus given a chance to become mass products. A permanent expo - which is also permanently updated or expanded.

The problem of aesthetics also exists on facades

In a densely built-up city like Frankfurt with a large number of multi-story buildings in a row, the roof areas of apartment buildings are often too small in relation to the inhabited space below. In order to generate enough electricity for everyone, a city must therefore look for additional surfaces. Facades are only suitable as alternative surfaces to a limited extent. In particular, old buildings in cities do not really want to be covered with them. An example from Zurich (see illustration): An art nouveau house was to be equipped with photovoltaics in the course of renovation. Since the roof area was too small, the facade was also used.

The new Frankfurt Bridge Quarter can show homeowners how aesthetically balanced or, above all, how invisible photovoltaics can be - on the roof, on the façade or integrated in other ways

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On Frankfurt's bridges, not only the roofs but also the facades of modern buildings are equipped with photovoltaics - with aesthetically suitable or inconspicuous modules.

The simplest solution when there is not enough space on the roof:
The photovoltaic modules are attached to the facade. Especially in modern architecture, the mirror effect of the glass layer above the photovoltaics can be used to elegantly integrate shiny black modules into the architecture.

The efficiency of such black monocrystalline panels is now over 20% - at least if the modules do not have to be bent. Bendable photovoltaic surfaces unfortunately have a lower efficiency than straight surfaces.

With selective scattering filters, even white photovoltaic surfaces can be created

A selective scattering filter reflects the visible light with a multitude of layers. In this way, the visible light is still perceived by us humans, while the infrared radiation is directed to the solar cells. The reflection of the white light component is achieved by an additional microstructure on the back of the film. However, as expected, this technology entails a loss of efficiency, so it generates somewhat less energy.

More than a third of the buildings on Frankfurt's bridges consist of modern architecture, which, in addition to elegant, smooth, dark facades, also likes to work with light, plain facades: as shown here in a visualization of a single-family house on Hanauer Landstrasse.

Boundry, Schweiz von Solaxess

Frankfurter Brücken, Hanauer Ldstr

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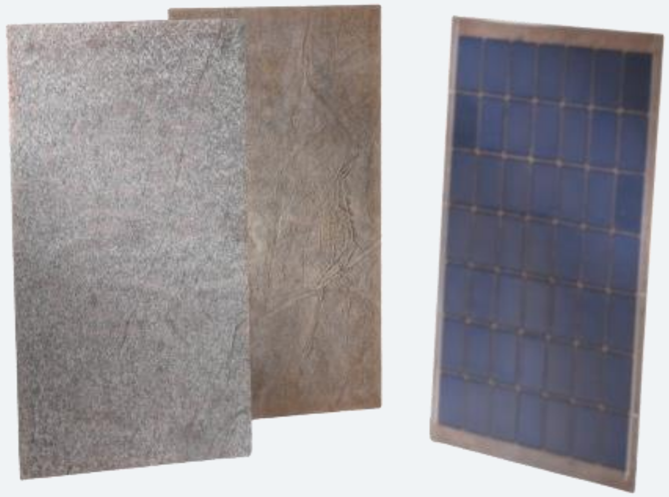
The public area can also be used: Small walls on the bridges are equipped with photovoltaics, which is not recognizable as such - but also has lower efficiency

Institutes, companies and start-ups around the world are working hard to find alternatives to conventional black photovoltaic modules. Like Frankfurt, many cities and municipalities have already calculated how much electricity they could generate through photovoltaics on their surfaces and by when they can become CO_2-neutral. If surfaces in public areas are renewed, as for example in the visualization on the chart, small walls can also be provided with photovoltaically activated surfaces to support the adjacent street lighting.

For example, some modules with a stone look do not reveal the photovoltaic technology behind them: the technology and the photovoltaic cells are hidden from view behind a printed front glass.



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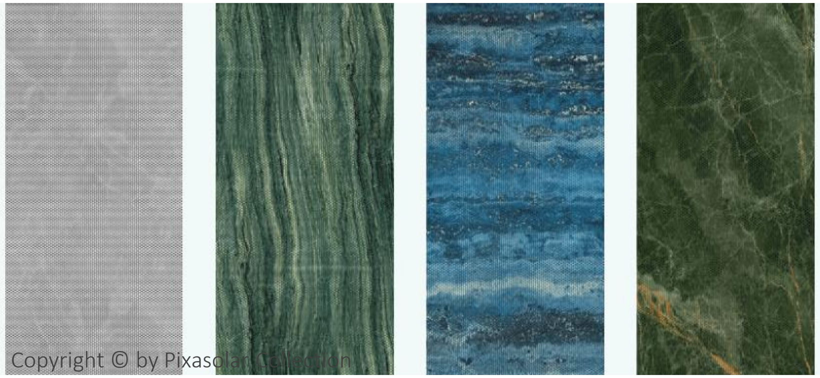
A colorful variety of photovoltaics can decorate both facades and other areas in the public space



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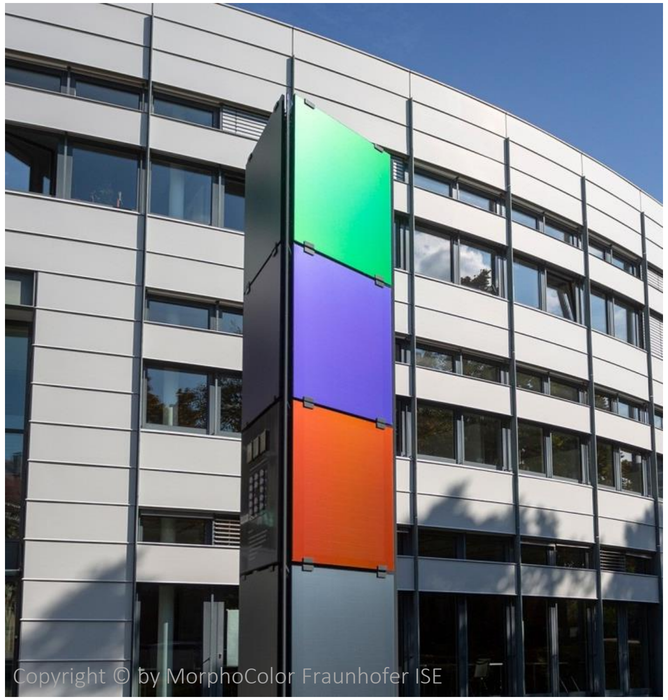
In addition to brightly colored printed front glass over the actual photovoltaic cells, there are now also technologies that can actually be used to produce colorful photovoltaic modules

While the colors of photovoltaic modules used to be rather muted and always had a gray or black cast, there is now a technology that the Fraunhofer Institute ISE from Freiburg has brought to the market: The so-called "MorphoColor modules".Here, the cover glasses of the photovoltaic modules are not colored with color pigments, but rather the physical effect of a butterfly wing is imitated: butterfly wings have a micrometer-fine surface structure that specifically reflects a color,. The Fraunhofer Institute has applied a similar surface structure to the back of the solar module glass layer. Depending on the structure, up to 7% of the incident light is reflected, causing the cover glass above the photovoltaics to be perceived as blue, red or green.



Elements in the public space can also be photovoltaically activated on the bridges and look very attractive in the process

Another way to enable optical diversity: curved photovoltaic surfaces instead of rigid flat modules. But here, too, efficiency losses must be accepted: The efficiency of this so-called "thin-film technology" is still below 15% today.

In addition to its flexibility, however, it has another advantage: the modules are significantly lighter and can therefore be used or installed in a variety of ways where the static requirements are not met for heavier modules.

For seating, pavilions or canopies in public spaces, many surfaces can be photovoltaically activated using thin-film technology.

Even the windows on the bridges are photovoltaically activated without the viewer noticing it

A new approach in the photovoltaic industry works with the principle of so-called "wave guiding". This is used on bridges, for example, for windows of buildings.

With wave guiding, the incident radiation is directed into the edge of a window with commercially available glass panes. Electrical energy is then generated in the edge via photovoltaic modules.

So the windows are their own little energy generators.

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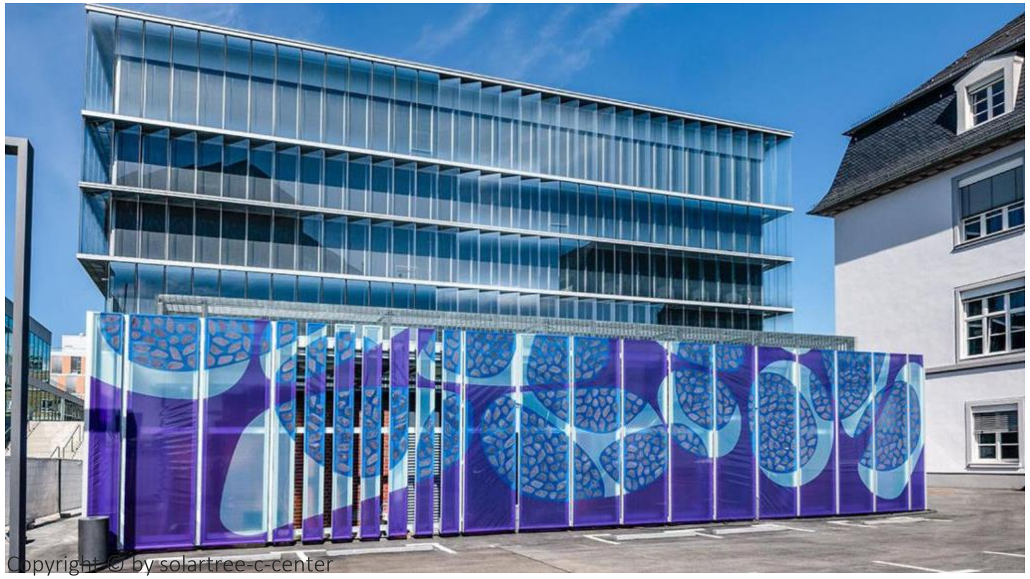
Photovoltaics are also planned on the bridges in the artistic area - however, the efficiency of the optically beautiful modules is usually relatively low



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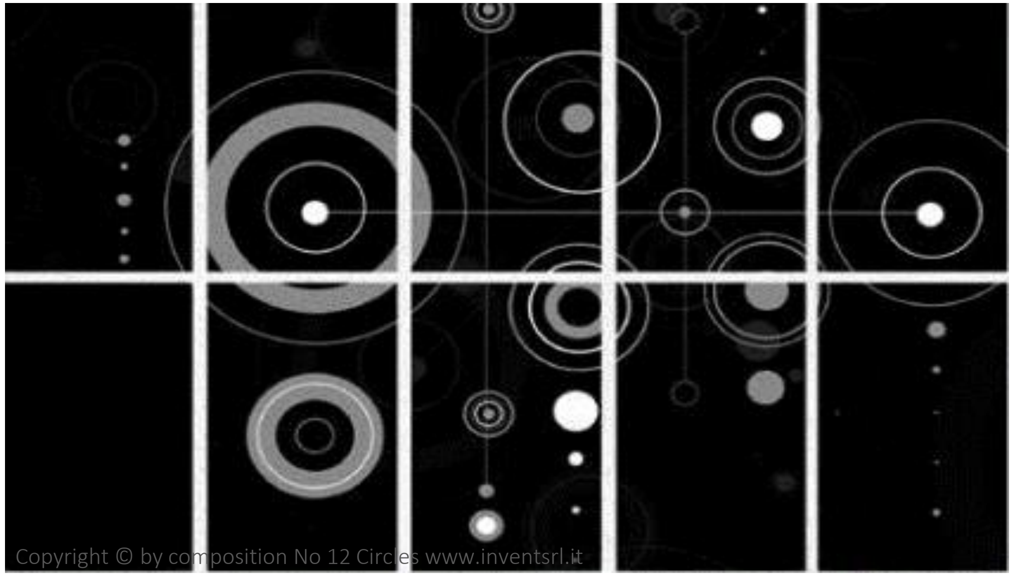
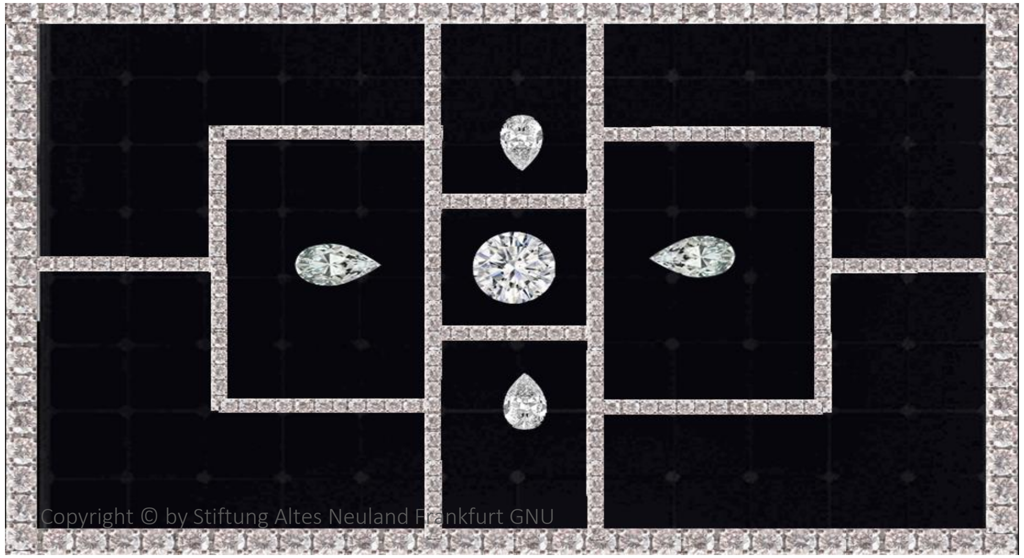
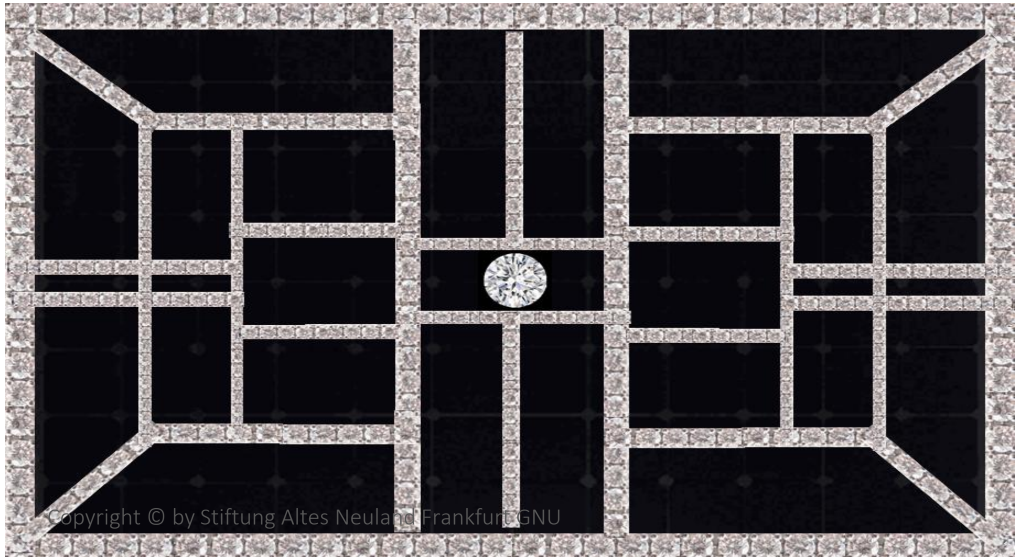


Because colorful artistic photovoltaics is not as effective as black. Therefore, on the bridges there are also photovoltaic artworks in black.





The photovoltaic harvest from so many surfaces on the bridges can only be used optimally with the help of sophisticated control systems

The new Frankfurt Bridges neighborhood can show homeowners how beautiful and, above all, invisible rooftop photovoltaics can be and how efficient it is for all aspects of life, including mobility.

An intelligent control system is being developed on the bridges for this purpose. In this way, an entire neighborhood can be supplied with the cheapest electricity, both for its infrastructure and for modern "luxury processes", such as moving garbage cans, bridge vehicles on call, automated carrying service for groceries (no more lugging) and much more - without "wasteful" use of electricity.

As soon as the electricity demand on the bridges is covered, surplus electricity produced by the photovoltaic modules is first stored in batteries or offered to the electricity-powered vehicles next to the bridges, which can "refuel" with electricity at the charging stations on the bridge piers. In addition, excess electricity generated is used to produce hydrogen. The green hydrogen is consumed by the H_2 -powered vehicles on the Frankfurt bridges, and surpluses are stored to be used in winter for power and heat generation by means of fuel cells.

Only when this demand on and along the bridges is also covered, all the bridges' energy storage systems are filled and there is still surplus electricity, will it be fed back into the grid of the local electricity supplier Mainova: There are therefore no individual invoices per building with the supplier Mainova, but only after the bridge-internal "netting" has taken place is there a bridge balancing with Mainova.

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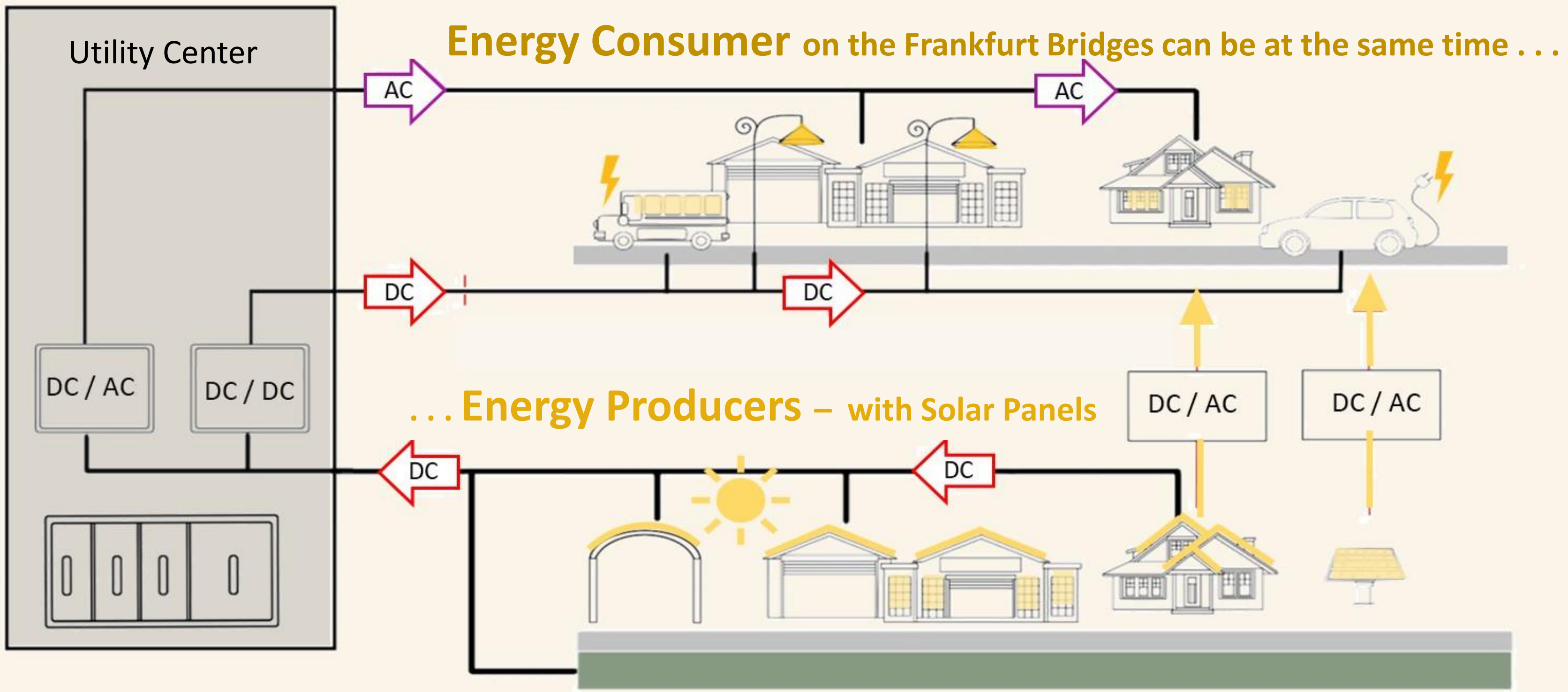
An intelligent control system is being developed on the bridges for the direct use of the photovoltaic electricity generated there



The photovoltaic modules on the bridges produce direct current (DC), which, however, cannot be used directly by the electricity consumers on the bridges, but must either be converted into suitable direct current with a different voltage or - for some types of end consumption - converted into alternating current (AC). In the case of so-called stand-alone solutions (generating and consuming elements form an "island" - e.g. in the case of street lighting with integrated photovoltaics), this is done without detours; however, the majority of the electricity produced on the bridges is first diverted to bridge-internal supply nodes, the "supply centers", where it is converted on a larger scale and centrally before being sent to the consumers.

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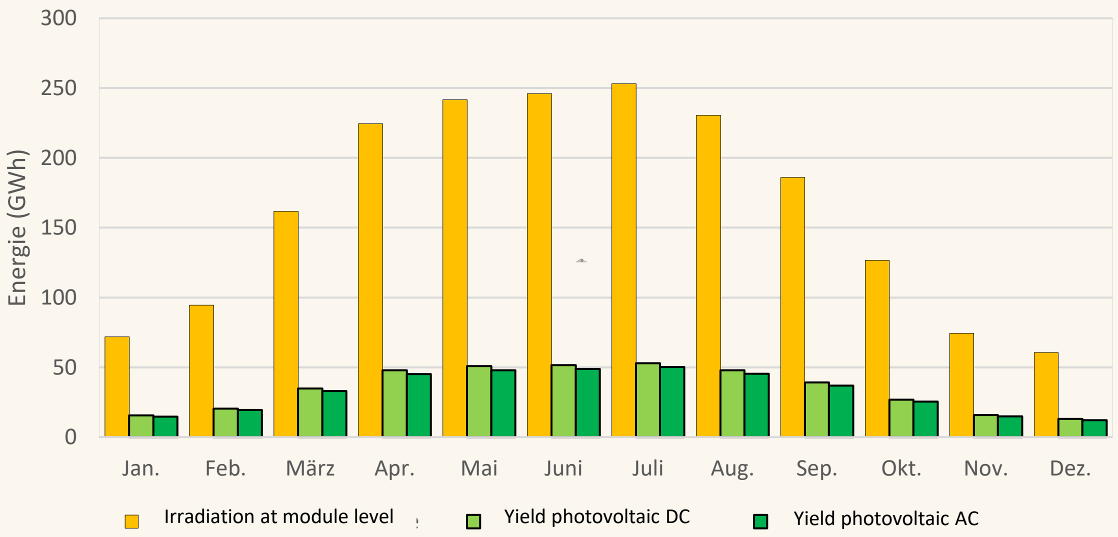
417 GWh/a of electricity can be generated by photovoltaics on and next to the bridges - simulated with conservative forecast values.

Simulations were performed with 25.5% efficiency of the PV modules. Conservatively, 4.5% loss was assumed, i.e. from a total irradiation of 1.971 GWh/a, approx. 21% was assumed as result efficiency on module level:
With complete DC/AC conversion, 5% (about 23 GWh/a) electricity would be lost.

This results in a total generation of approx. 417 GWh of electricity per year by the solar modules on and next to the bridges. Even after complete AC transformation, 392 GWh/a of this could still be used.

Power generation

Name	Unit	Year	Jan.	Feb.	March	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Irradiation at module level	GWh	1971	72	95	162	224	242	246	253	230	186	127	74	61
Yield photovoltaic DC	GWh	417	16	21	35	48	51	52	53	48	39	27	16	13
Yield photovoltaic AC	GWh	394	15	19	33	45	48	49	50	45	37	25	15	12

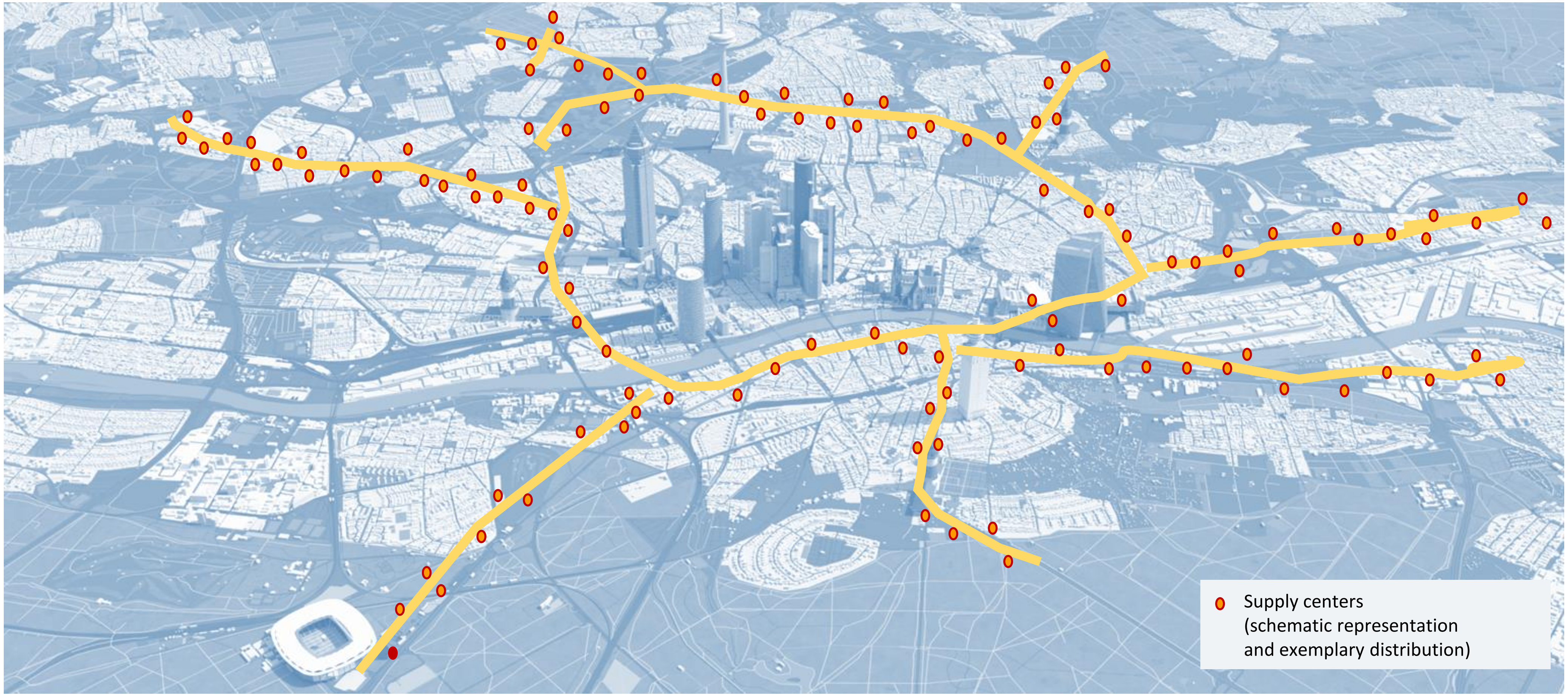


The maximum electricity yield is recorded in July, when it is four times higher than in December - the month with the lowest electricity production.

This graph illustrates the need to supplement the Frankfurt Bridges power system with a storage system that stores summer surpluses for winter.

The bridge quarter gets supply centers along the bridges - in them take place storage, conversion and processing of energy, but at the same time they serve as infrastructure for drinking water, firefighting water, communications, etc.

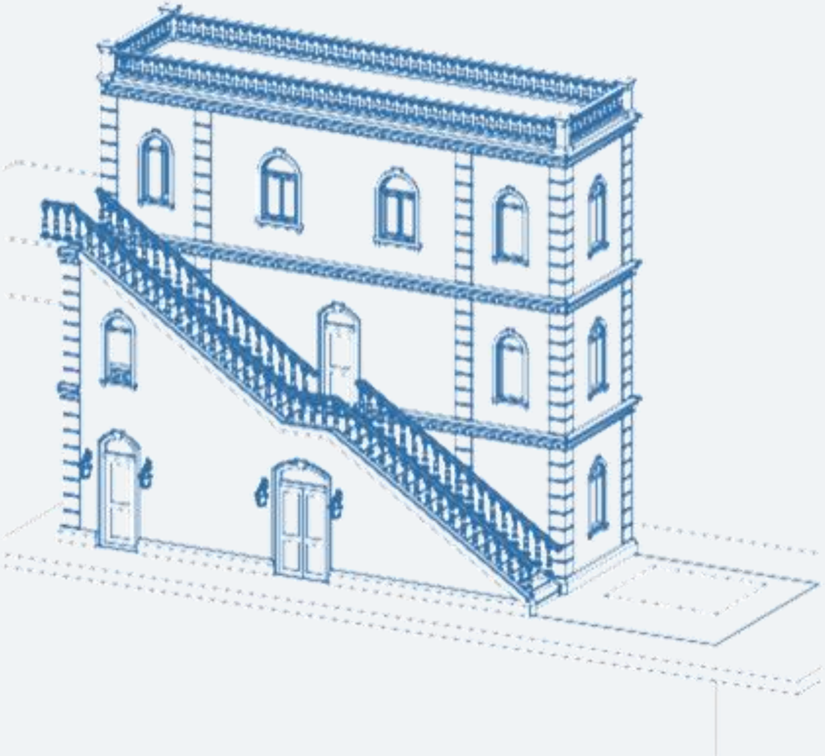
The energy from photovoltaic systems is not used directly for buildings, lanterns, etc. on the bridges, but is first routed to the so-called supply centers: approximately every 500 to 1000 m, there are centers to the right or left of the bridges, where many lines converge and the excess energy is distributed intelligently and efficiently.

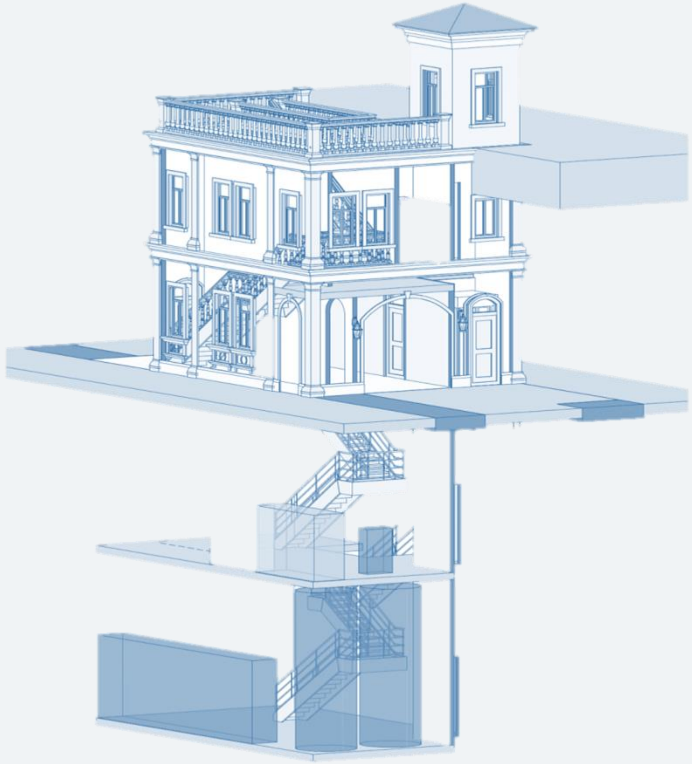


The term "supply center" suggests the worst, but the centers are "undercover" on the move: either ultra-modern or handcrafted - like aesthetic pearls along the bridges

At pedestrian level, the utility centers are kept extremely slim and space-saving - but in return they are up to two basement levels deep underground

Each supply center is stylistically adapted to the surrounding buildings: If the surrounding area is characterized by old buildings, then the supply centers dress up as Wilhelminian villas; in modern surroundings, on the other hand, they are ultra-modern, but artistically designed: through lighting effects, graffiti painting, modern art, natural stone cladding or other stylistic means of art.





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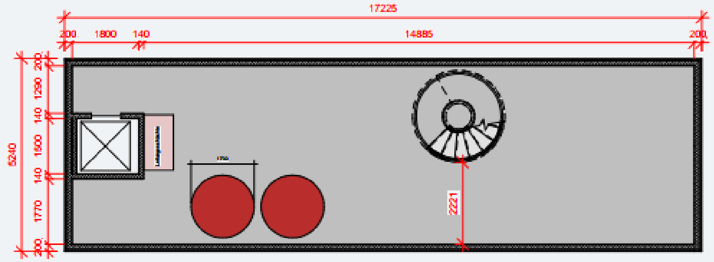
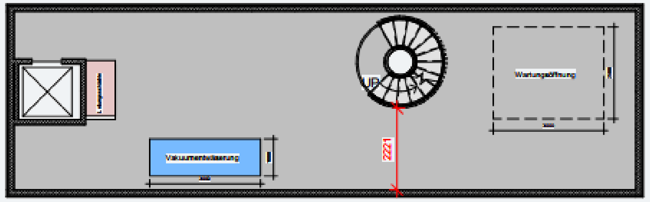
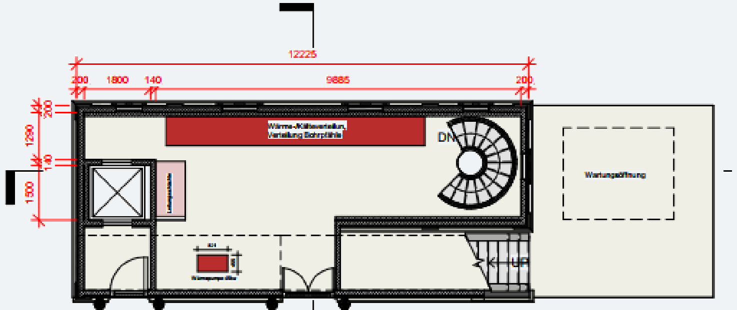
Some utility centers have not only one basement, but have two basements



Floor plan U2 1:100

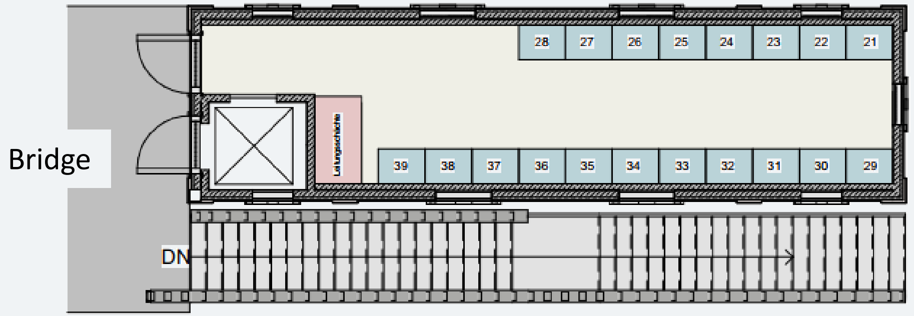


Floor plan U1 1:100

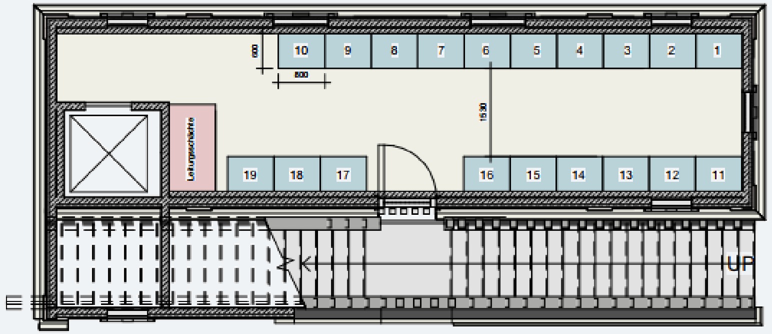


Floor plan EG 1:100

The interior consists of switch cabinets, computers, pumping units and much more.

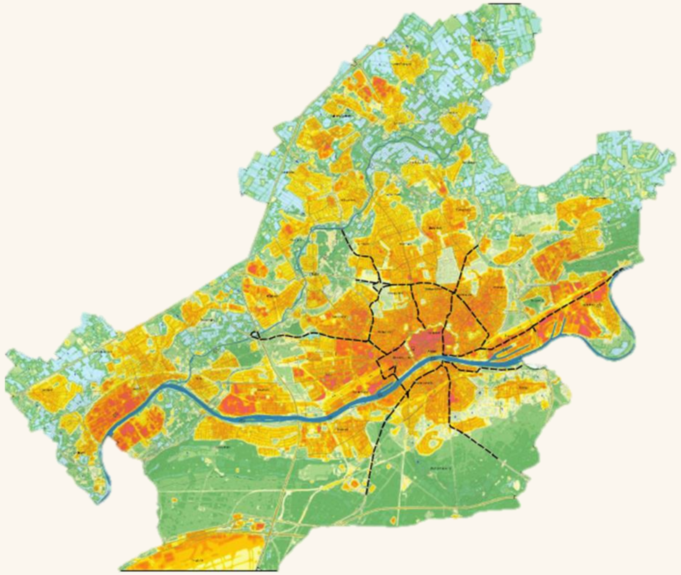


Floor plan bridge level 1:100



Floor plan platform level 1:100

The Frankfurt Bridges Quarter has the great advantage that it runs through Frankfurt like a network



Electricity surpluses of the bridges can thus also be distributed to other customers.

During the day, if excess electricity is produced in one part of the bridge network - e.g. on an apartment building - without being needed, it can be transported further in the local network to another customer on the bridges, e.g. a restaurant that is in peak operation.

If electricity then remains, Li-ion as well as redox flow batteries of the bridges can be charged or conversion to hydrogen can also be used for energy storage.

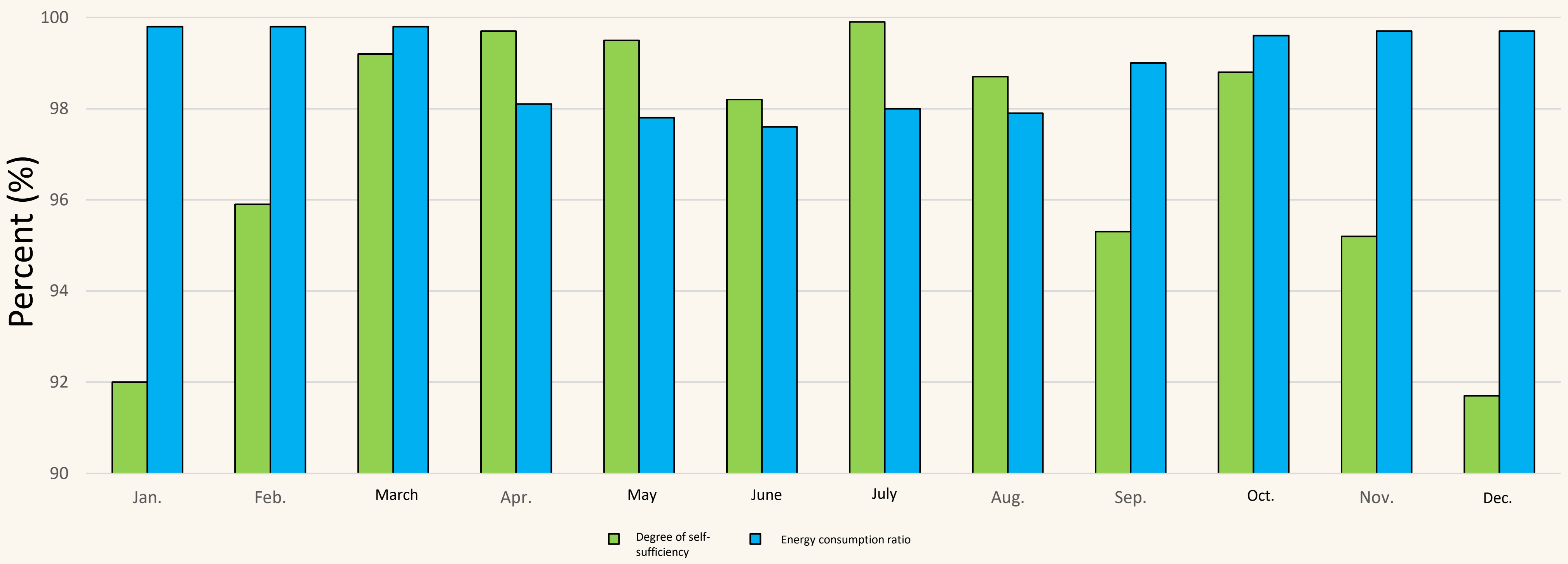
Moreover, the distribution of excess electricity can take place not only on the bridges within the neighborhood, but also, for example, by charging electrically powered cars on and next to the bridges.

When all consumers on and along the bridges are supplied and their own storage facilities are full, they have to feed into the network of the municipal utility: This means that the bridge residents or users are not billed individually by Mainova, the supplier, but rather that internal netting within the neighborhood is the number one priority, followed by the filling of the bridge's own storage facilities and the supply of vehicles along the bridges. Only at the very end is there netting with Mainova via the bridge-internal supply nodes, the "supply centers".

The Frankfurt bridges are almost self-sufficient: both the degree of self-sufficiency and the self-consumption ratio are over 90% and almost 100% respectively

The **degree of** self-sufficiency describes the ratio between self-supply and total consumption. The Frankfurt bridges can cover almost all their electricity needs through self-supply.

In this way, power exchange with the urban power grid is minimized: Surplus electricity is either stored in batteries or hydrogen is produced with it - both of which significantly reduce the grid feed-in. This leads to a high **self-consumption ratio:** self-consumption is covered by self-power production to almost 100%.



Name	Unit	Year	Jan.	Feb.	March	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Degree of self-sufficiency	%	97,7	92	95,9	99,2	99,7	99,5	98,2	99,9	98,7	95,3	98,8	95,2	91,7
Energy consumption ratio	%	98,6	99,8	99,8	99,8	98,1	97,8	97,6	98	97,9	99	99,6	99,7	99,7

The Frankfurt bridges can not only ensure their own power supply and provide surplus electricity to neighboring quarters - rather, they can also make a thermal energy contribution

Frankfurt is located at a favorable latitude for photovoltaics

Photovoltaic systems use sunlight to generate electricity.

So you might think "the more sun, the better for a photovoltaic system"; that would mean that, theoretically, the desert would have to be the best place to get really high levels of photovoltaic energy.

However, the performance of photovoltaics decreases as soon as it gets too hot

Only when photovoltaic modules are cooled, e.g. by wind blowing beneath them, do they achieve optimum efficiency levels.

Germany thus has comparatively good photovoltaic potential, because the sun does not shine as strongly here as in the desert and there is plenty of cooling wind on sunny days in Central Europe.

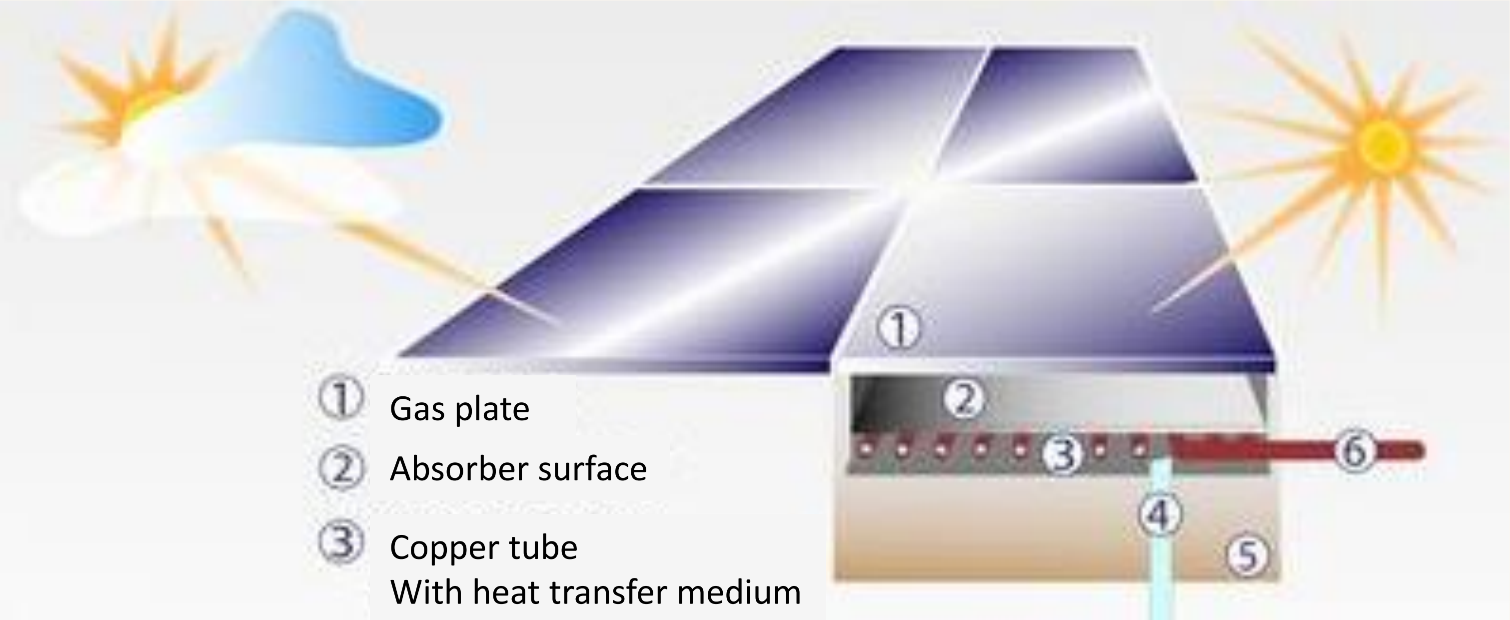
Photovoltaics on the bridges is therefore mostly back cooled

Photovoltaics can be back-cooled not only with air, but also with brine in solar thermal pipes installed under the photovoltaic layer. This kills two birds with one stone on the same roof surface: the photovoltaics are back-cooled, and the brine behind them is still heated. This is therefore mostly used on bridges.

Accordingly, not only electricity from photovoltaics is used on the Frankfurt Bridges, but also heat from solar thermal energy

Solar thermal systems use the sun's heat to generate energy. However, this requires relatively continuous, intensive solar radiation if you want to heat an entire house with it. Accordingly, solar thermal energy is usually only used in Central Europe to supplement other energy systems, i.e. to support normal heating in the basement - as is the case on the Frankfurt Bridges.

The majority of the solar modules on the bridges are designed as so-called hybrid collectors: They can generate electricity through photovoltaics on their surface and at the same time collect thermal energy through pipes underneath. In summer, the heat is stored underground in the so-called Borehole Thermal Energy Storage (BTES); in winter, it is used to support the heat pumps with the (rather lukewarm water).



Heat surpluses in summer can be stored in the ground with the help of probe fields along the Frankfurt bridges

A potential storage of excess thermal energy is near-surface geothermal probe fields, which will be installed during the construction project where the road surface has to be renewed anyway for the construction of the bridges.

Can you actually send solar heat into the ground and store it there for cold days?

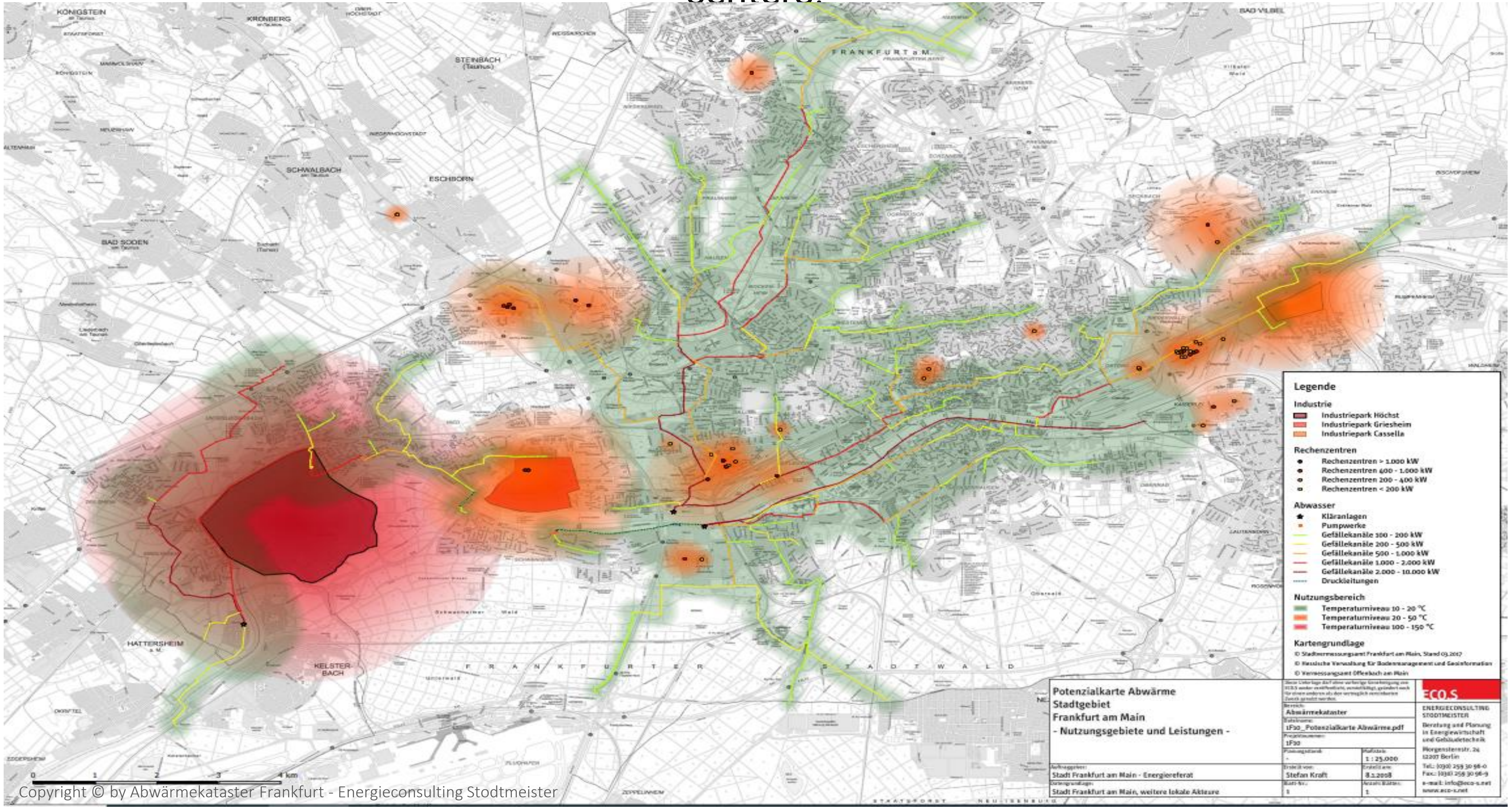
Doesn't the heat that you send down in the summer get lost immediately down in the ground?

Does it actually stay around the column piles or geothermal probes and can be used for heating weeks or months later?

And if the heat remains in the soil: Wouldn't the groundwater in the soil layer then heat up?

The answer is provided by coupling systems of solar and geothermal energy: their mode of operation in the Frankfurt bridges has been simulated as part of a study, as a prototype for their functioning in the "city of the future" with an "energy infrastructure of the future".

And there are other sources of about 190 MW of heat in Frankfurt that can be stored in the ground with the help of the bridges: 100 MW of heat from wastewater, 40 MW of waste heat from industrial parks and 50 MW of waste heat from data centers.



Old New Territory
Frankfurt

Conclusion: The urban energy revolution can be realized on Frankfurt's bridges

From photovoltaics to solar thermal and geothermal energy: the city's complete potential for renewable energy can be used on the bridges. In addition, the unused waste heat from data centers and industrial parks is efficiently co-used. In terms of construction, everything is planned directly when the bridge is built: from equipping all surfaces with solar thermal energy, to equipping the bridge network with supply centers - to geothermal activation of the bridge piers.

In the process, transferability to the rest of the existing city is ensured: Hybrid collectors or photovoltaic modules must be aesthetically pleasing or invisible, depending on the surroundings - as a showcase, so to speak, to motivate homeowners to follow suit.

The surplus electricity will be made available to the rest of the city, and the excess heat will benefit buildings with heat pumps along the bridges, among other things. The handover of the bridge corpus, including lines, to the Frankfurt municipal utility Mainova ensures that the energetically modern bridge world is interlinked with the rest of the city.

Old New Territory
Frankfurt

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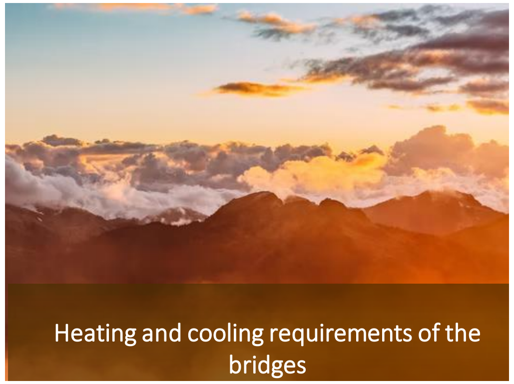
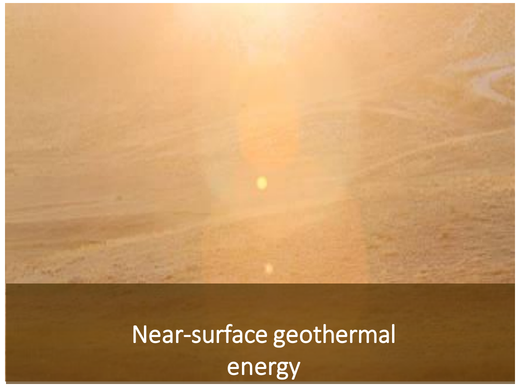
Electricity demand on the Frankfurt bridges


Photovoltaics as quarter power


Heating and cooling requirements of the bridges


Near-surface geothermal energy


The energy infrastructure of the future


The bridge world

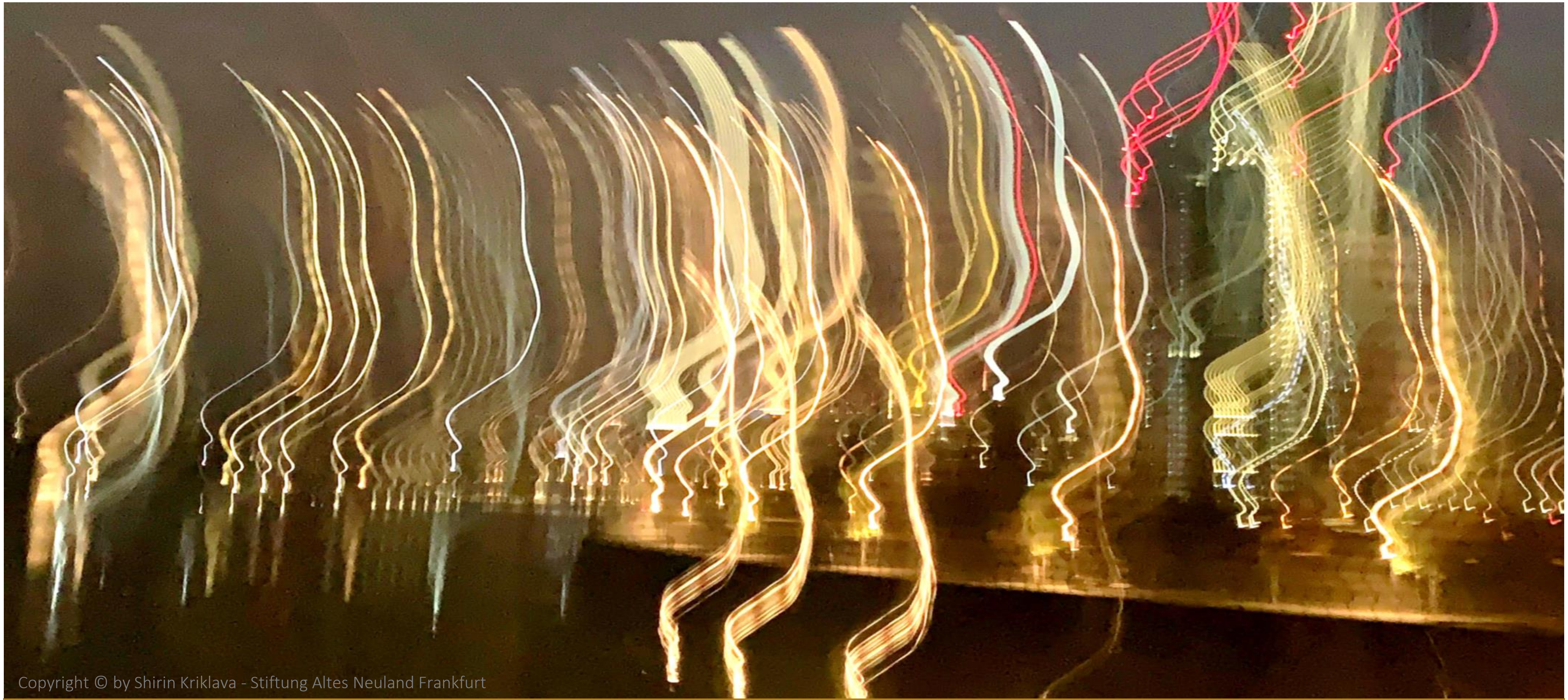

Sustainability through technology


The Co2 balance of bridges

EMPLOYEES

Architecture	Geoinformation	Urban climate - world climate	Water	Law	**Critical sparring partners:**
Image & photo	Green & Nature	Statics	Packing	Finance	Professors
Bridges	Communication	Transportation	Webpage & Design	Implementation	Professionals
Energy	Art & Culture	Technology & IT			Inspirers & Supporters

Power Requirement of the Bridges



Frankfurt's bridges require around 140 GWh/a of electricity - electricity consumption from hot water, heat pumps and autonomous driving included!

Of the 140 GWh of electricity per year, about 53 GWh/a are used by Bridge households with about 35,000 Bridge residents. Around 22 GWh/a are consumed by businesses such as restaurants, educational institutions, etc.. Of the remaining 65 GWh/a, 58 GWh/a are used by bridge traffic, and 7 GWh/a are consumed by bridge infrastructure such as elevators, street lighting, control technology, pumps, etc.

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Content: Composition of the electricity demand on the Frankfurt bridges

The 35,000 Bridge residents consume about 1,500 KWh/a per capita in their households - including heat pumps for space heating and cooling- or a total of about 53 GWh per year, because only the most modern technology and extremely energy-saving appliances are installed in Bridge homes.

A total of 22 GWh/a is required for 275,000 m^2 of non-residential building space, and restaurants, sports facilities, educational institutions, and more must also be equipped with energy-saving devices and also sensor technology from the start, so that everything is controlled on a demand basis and only comes on when it is used.

With 14 hours of travel time per day all year round, the 400 bridge vehicles consume 58 GWh/a of drive energy (plus around 2 GWh for control technology). The comparatively low power consumption of approx. 85 kWh/100 km for electric-powered vehicles and approx. 230 kWh/100 km for H_2 -powered vehicles is due to the lightweight construction of the bridge vehicles and the smooth operation of the autonomous traffic.

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The largest electricity consumers on the Frankfurt bridges are the buildings with a total of 75 GWh/a, followed by the e-vehicles with 58 GWh/a

Category					TOTAL GWh/a
Residential	76%	# People	Power consumption (kWh/a)	Total electricity demand (GWh/a)	
		35.000	1.080	37,79	53
Heat pumps heating for residential buildings				10,00	
Heat pumps cooling for residential buildings				4,60	
Elevators (residential buildings)	470	408		0,19	
Non-residential	24%	Area (m^2) / Quantity	spec. electricity demand (KWh/m^2 a)	Total electricity demand (GWh/a)	
Cafés, kiosks, teahouses, etc. Small restaurant	12%	33.001	137	4,51	22
Restaurants, bistros	10%	27.501	137	3,76	
Grocery stores (small/large)	11%	30.251	79	2,39	
Special sales stores (art, organic flowers, etc.)	10%	27.501	27	0,75	
Micro-enterprises (repair café, cooking school)	4%	11.000	40	0,44	
Service providers (hairdresser, cosmetics, cobbler, etc.)	6%	16.501	62	1,02	
Div. offices (landscapers etc. max. 5 employees)	1%	2.750	33	0,09	
Medical practices of all kinds	5%	13.751	40	0,55	
Sports activity (fitness, dance, gymnastics, etc.)	4%	11.000	74	0,82	
Swimming pools with special focus (3 pieces)	3%	8.250	83	0,69	
Music pavilion, hobby pop-up, theater, other. Culture	6%	16.501	31	0,47	
Crèches/kindergartens/education	4%	11.000	28	0,31	
Primary/secondary schools	3%	8.250	31	0,25	
IT College	10%	27.501	41	1,13	
Academy of Arts and Crafts	9%	24.751	41	1,01	
Special shelters (women's shelter, etc.)	2%	5.500	69	0,38	
Heat pump for non-residential buildings				3,20	
Elevators (commercial)	215	505		0,11	
Facilities/Equipment	Quantity		Power consumption (kWh/a)	Total electricity demand (GWh/a)	
Elevators (Public)	400		832	0,33	7
Freight elevators (supermarkets)	60		506	0,03	
Public lighting (on bridge)	9000		103	0,92	
Public lighting (below bridge)	9000		164	1,48	
Separation systems	400		170	0,07	
Sliding door transitions	600		127	0,08	
Ticket vending machines and others	209		1.168	0,24	
Packing rondelle	500		781	0,39	
Infoscreens	209		1.168	0,24	
Irrigation & Drainage				2,00	
Automation, control, communication, network technology				2,00	
Vehicles	Quantity		Power consumption per vehicle (kWh/100 km)	Total electricity demand (GWh/a)	
Electric-powered vehicles on the bridges	200		85	15,80	58
H2-powered vehicles on the bridges	200		230	41,90	
SUM					140

The residential buildings on the bridges are comparatively economical in electricity consumption

1.15 million square meters of building space are being created on the Frankfurt bridges, 875,000 m^2 of which is residential space, the rest is a colorful mix of areas for education, culture, sports, medical professions, gastronomy or ecologically valuable supermarkets and stores.

The 35,000 inhabitants of Frankfurt's bridges require around 53 GWh/a for lighting, household appliances, etc. and hot water as well as heat pumps. Compared to Frankfurt, this is economical, as the 750,000 inhabitants of Frankfurt's households consume 900 GWh/a, and this despite the fact that only a small proportion of these households have heat pumps - most buildings in Frankfurt still have gas heating. If they were all heated with heat pumps like the bridge households, the electricity demand would be significantly higher.

The fact that the electrically driven heat pumps of the bridge buildings do not significantly increase the electricity consumption of the bridge households is primarily due to the coupling with geothermal energy, solar thermal energy and waste heat from data centers, which increases the COP (Coefficient Of Performance) of the heat pumps: The electricity consumption of heat pumps for space heating and cooling for all buildings is only 17.8 GWh/yr.

Electricity mirror Germany 2020/2021

Properly equipped households consume up to 50% less electricity

Building type	Hot water	Persons in the Household	A (gering)	B	C	D	E	F	G (sehr hoch)
House	Without power	1	bis 1.300	bis 1.600	bis 2.000	bis 2.500	bis 3.200	bis 4.100	über 4.100
		2	bis 2.000	bis 2.400	bis 2.800	bis 3.000	bis 3.500	bis 4.200	über 4.200
		3	bis 2.500	bis 3.000	bis 3.400	bis 3.700	bis 4.200	bis 5.000	über 5.000
		4	bis 2.700	bis 3.300	bis 3.700	bis 4.000	bis 4.700	bis 5.800	über 5.800
		5+	bis 3.200	bis 4.000	bis 4.500	bis 5.000	bis 6.000	bis 7.500	über 7.500
	With power	1	bis 1.500	bis 1.900	bis 2.300	bis 2.900	bis 3.500	bis 5.000	über 5.000
		2	bis 2.400	bis 3.000	bis 3.400	bis 3.800	bis 4.500	bis 6.000	über 6.000
		3	bis 3.000	bis 3.500	bis 4.000	bis 4.800	bis 5.600	bis 7.000	über 7.000
		4	bis 3.500	bis 4.000	bis 4.800	bis 5.500	bis 6.400	bis 8.000	über 8.000
		5+	bis 4.000	bis 5.000	bis 6.000	bis 6.800	bis 8.000	bis 10.000	über 10.000
Apartment	Without power	1	bis 800	bis 1.000	bis 1.200	bis 1.500	bis 1.600	bis 2.000	über 2.000
		2	bis 1.200	bis 1.500	bis 1.800	bis 2.100	bis 2.500	bis 3.000	über 3.000
		3	bis 1.500	bis 1.900	bis 2.200	bis 2.600	bis 3.000	bis 3.700	über 3.700
		4	bis 1.700	bis 2.000	bis 2.500	bis 2.900	bis 3.500	bis 4.100	über 4.100
		5+	bis 1.700	bis 2.300	bis 2.800	bis 3.500	bis 4.200	bis 5.500	über 5.500
	With power	1	bis 1.000	bis 1.400	bis 1.600	bis 2.000	bis 2.200	bis 2.800	über 2.800
		2	bis 1.800	bis 2.300	bis 2.600	bis 3.000	bis 3.500	bis 4.000	über 4.000
		3	bis 2.500	bis 3.000	bis 3.500	bis 4.000	bis 4.500	bis 5.500	über 5.500
		4	bis 2.500	bis 3.200	bis 4.000	bis 4.500	bis 5.000	bis 6.000	über 6.000
		5+	bis 2.400	bis 3.500	bis 4.300	bis 5.200	bis 6.200	bis 8.000	über 8.000

The household of the future operates with optimized power consumption

In keeping with the trend toward smaller households, over half of bridge housing units are 2- to 3-person households.

According to Stromspiegel, electricity consumption per person in a low-electricity-consuming optimized two-person apartment (with hot water provided by electricity, as is also planned on the bridges, but without a heat pump) is currently still around 1,800 kWh/yr.

When calculating the electricity demand of the 35,000 bridge residents, it must be taken into account that they live in buildings with different sizes or numbers of floors

The total electricity demand for the residential buildings on the bridges (excluding heat pumps) is about 38 GWh/a. With 35,000 bridge residents, the average electricity consumption per person is accordingly around 1,100 kWh/a.

Residential	Share Building type	Quantity People	Share Residents	Share of building type /Residents	Number Of People	Electricity demand (kWh/p)	Electricity demand (GWh/a)
<=2.5 Floors (House)	65%	1	20%	13.0%	4,550	1,500	6.8
		2	50%	32.5%	11,375	2,400	13.7
		3	20%	13.0%	4,550	3,000	4.6
		4	10%	6.5%	2,275	3,500	2.0
>2.5 Floors (Multi-family houses)	35%	1	20%	7.0%	2,450	1,000	2.5
		2	50%	17.5%	6,125	1,800	5.5
		3	20%	7.0%	2,450	2,500	2.0
		4	10%	3.5%	1,225	2,500	0.8
			Sum	100%	35,000		37.8

Culinary and education take up the largest share of space on Frankfurt bridges

Cafes, kiosks, teahouses, etc. Small restaurants	12%
Restaurants, bistros	10%
Grocery stores (small/large)	11%
Special sales stores (art, organic flowers, etc.)	10%
Small businesses (repair café, cooking school).	4%
Service providers (hairdresser, cosmetics, cobbler, etc.)	6%
Div.offices (landscapers etc. max 5 employees)	1%
Medical practices of all kinds	5%
Sports activity (fitness, dance, gymnastics, etc.)	4%
Swimming pools with special focus (3 pieces)	3%
Music pavilions, hobby pop-ups, theater other culture.	6%
IT-College	10%
Academy of Arts and Crafts	9%
Crèches/kindergartens/education	4%
Primary/secondary schools	3%
Special shelters (women's shelter, etc.)	2%

Area shares of the individual sectors in the total area of the Frankfurt bridges

Non-residential buildings consume slightly more electricity on average than private households

An electricity consumption blended value can be calculated for the 275,000 m^2 of mixed color "non-residential" space:

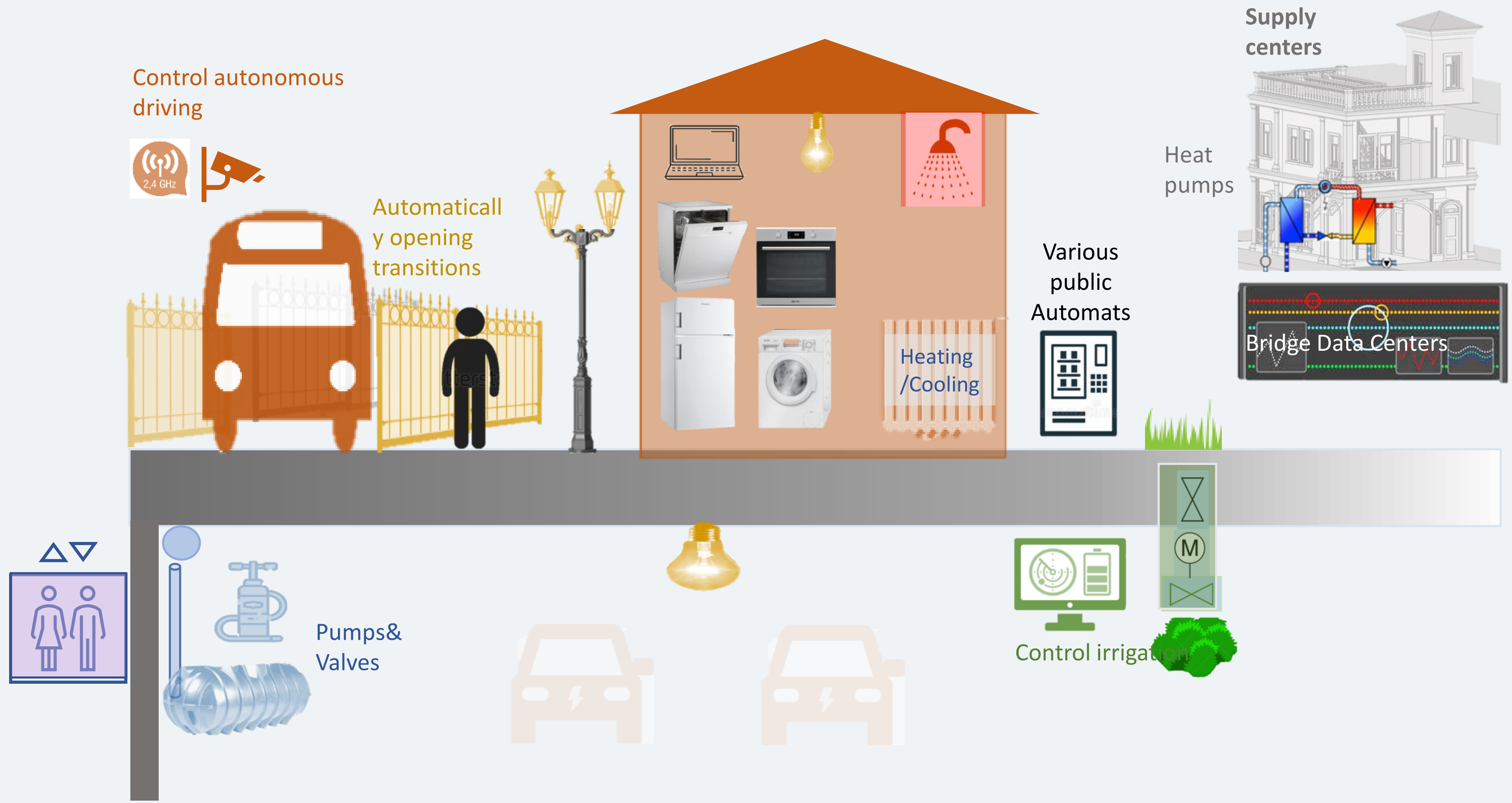
Weighting the industry-specific electricity consumption per square meter by the square meter share of each industry on the bridges, we arrive at an average (optimized) electricity consumption of around 80 kWh/m^2 a, including heat pump electricity consumption, which is used to provide heating and cooling.

For the non-residential areas on the bridges, this results in a total electricity consumption of approximately 22 GWh/a.

The specific electricity demand changes according to the type of use: gastronomy is the main electricity consumer in the non-residential buildings on the bridges

Non-residential	Percent/ Number	Area (m2) / Number	spec. electricity demand (kWh/m2a)	Electricity demand (GWh/a)	Total (GWh/a)
Cafes, kiosks, teahouses, etc. Small restaurant	12%	33.001	137	4,51	22
Restaurants, bistros	10%	27.501	137	3,76	
Grocery stores (small/large)	11%	30.251	79	2,39	
Special sales stores (art, organic flowers, etc.)	10%	27.501	27	0,75	
Micro-enterprises (repair café, cooking school)	4%	11.000	40	0,44	
Service providers (hairdresser, cosmetics, cobbler, etc.)	6%	16.501	62	1,02	
Div. Büros (Landschaftsgärtner etc. max. 5 Mitarbeiter)	1%	2.750	33	0,09	
Medical practices of all kinds	5%	13.751	40	0,55	
Sports activity (fitness, dance, gymnastics, etc.)	4%	11.000	74	0,82	
Swimming pools with special focus (3 pieces)	3%	8.250	83	0,69	
Music pavilion, hobby pop-up, theater, other. Culture	6%	16.501	31	0,47	
Crèches/kindergartens/education	4%	11.000	28	0,31	
Primary/secondary schools	3%	8.250	31	0,25	
IT-College	10%	27.501	41	1,13	
Academy of Arts and Crafts	9%	24.751	41	1,01	
Special shelters (women's shelter, etc.)	2%	5.500	69	0,38	
Heat pump for non-residential buildings				3,10	
Elevators (commercial)	240	505		0,11	

Other infrastructure such as street lighting, controls, pumps, elevators, etc. consume comparatively little electricity, totaling 7 GWh/a

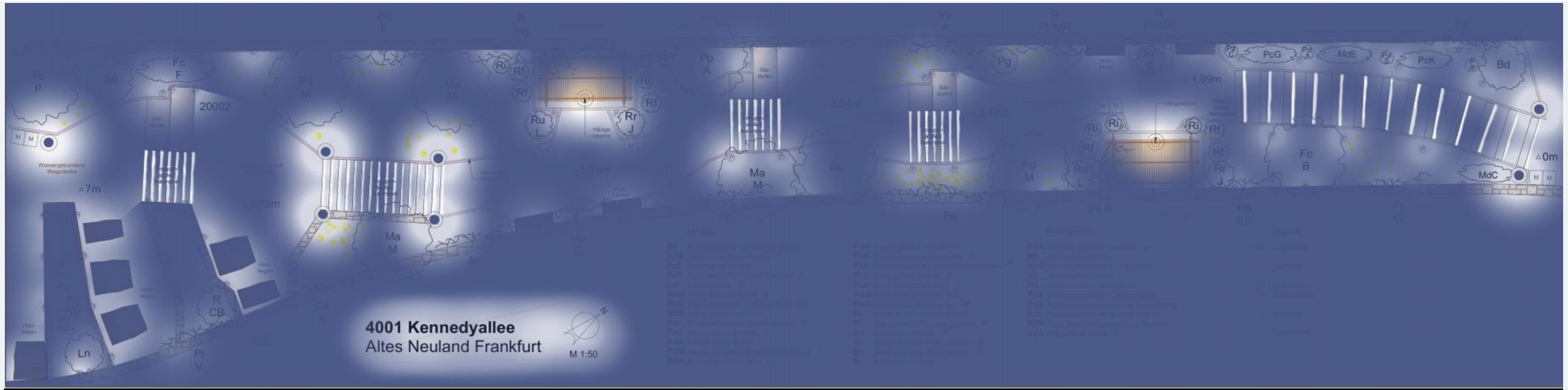


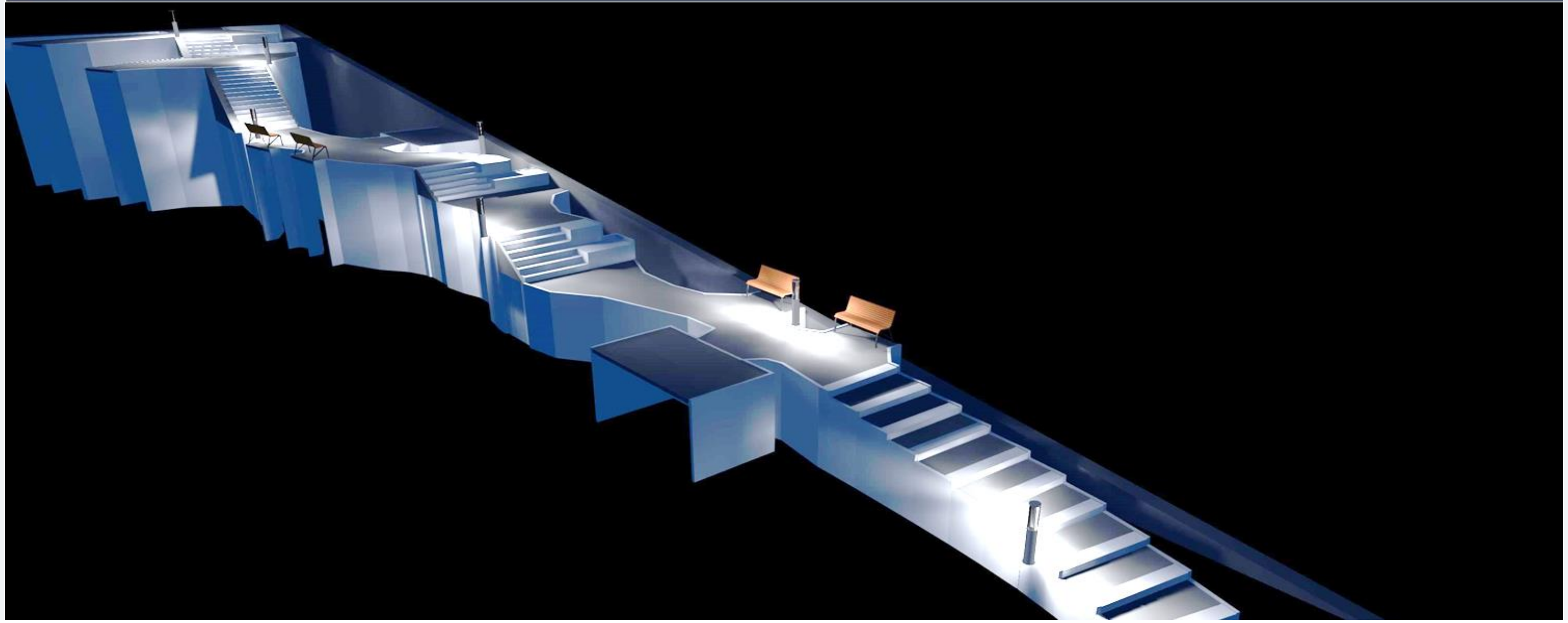
The bridge infrastructure consumes approx. 7 GWh/a - automation and control are the main electricity consumers, followed by lighting on and under the bridges.

Facilities/Equipment	Quantity	individual power consumption (kWh/a)	Total electricity demand (GWh/a)
Elevators (Public)	400	832	0,33
Public lighting (on the bridges)	9.000	103	0,92
Public lighting (under the bridges)	9.000	164	1,48
Separation systems	400	170	0,07
Sliding door transitions	600	127	0,08
Ticket vending machines and others	209	1.168	0,24
Packing rondelle	500	781	0,39
Infoscreens	209	1.168	0,24
Irrigation & Drainage			2,00
Automation, control, communication, network technology			2,00
TOTAL			7

As part of the four- to five-year preliminary planning phase for the Frankfurt bridges, electricity consumption must be planned in detail in all areas

Example: Lighting design 200 m section Kennedyallee between railroad bridges and Paul-Ehrlich-Straße





The vehicles on the bridges transport around 40 million passengers per year - and consume 58 GWh of electricity p.a. to do so: Of these, 200 are e-vehicles and 200 are hydrogen vehicles.

The 400 vehicles on the bridges travel 14 hours a day at an average speed of 17.8 km/h. Each vehicle covers an average of 250 km per day.

The large bridge vehicles for multi-passenger transport run on hydrogen, while the smaller ones are pure e-cars.

According to the current state of development for both types of propulsion, the energy consumption for electricity-powered vehicles is 15 kWh/100 km and for hydrogen-powered vehicles 60 kWh/100 km: Both vehicle types are planned in lightweight construction, which means that their consumption is lower than that of current commercial (bus) models with alternative forms of propulsion.

Vehicles	Quantity	Power consumption per vehicle (kWh/100 km)	total electricity demand (GWh/a)	Total (GWh/a)
Electric-powered vehicles on the bridges	200	85	15,8	**58**
H_2 -Powered vehicles on the bridge	200	230	41,9	

The bridges generate around 417 GWh of electricity per year - but the bridges themselves and their vehicles consume only 140 GWh/a of this. The remaining surplus of around 190 GWh is used to supply vehicles on roads along the bridges.

127 GWh/a will be provided for electricity-powered vehicles along the bridges, and additional energy will be put into the production of 64 GWh/a of hydrogen for H_2 -powered vehicles along the bridges.

Meeting demand next to the bridges	Number of refueling per day	individual power consumption (kWh/a)	Total electricity demand (GWh/a)	Total (GWh/a)
H_2 -powered buses next to the bridges	80	736.000	59	191
H_2 -operated vehicles next to the bridges	50	96.000	5	
Electric-powered vehicles next to the bridges (300 days)	3.200	29.780	95	
Electricity-powered next to the bridges (365 nights)	1.000	32.000	32	

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Conclusion: The electricity demand on the bridges is already optimized during the construction of the quarter

Residential buildings, like non-residential buildings, are equipped with energy-efficient appliances and sensor technology for targeted appliance use. At 75 GWh/a, they consume about half of the electricity on the bridges.

The second-largest consumers are the hydrogen and electricity-powered vehicles on the bridges: they are very energy-efficient due to their light weight and optimized, low-brake routing, and require a total of 58 GWh/a.

At 7 GWh/a, bridge infrastructure consumes the smallest share of the total bridge electricity consumption of 140 GWh/a.

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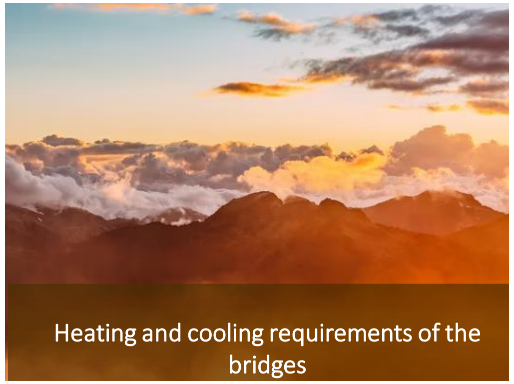
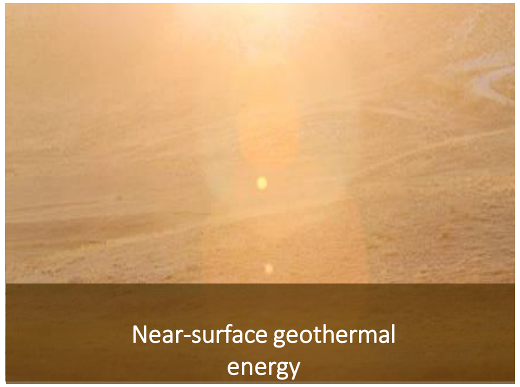
Electricity demand on the Frankfurt bridges


Photovoltaics as quarter power


Heating and cooling requirements of the bridges


Near-surface geothermal energy


The energy infrastructure of the future


The bridge world


Sustainability through technology


The Co2 balance of bridges

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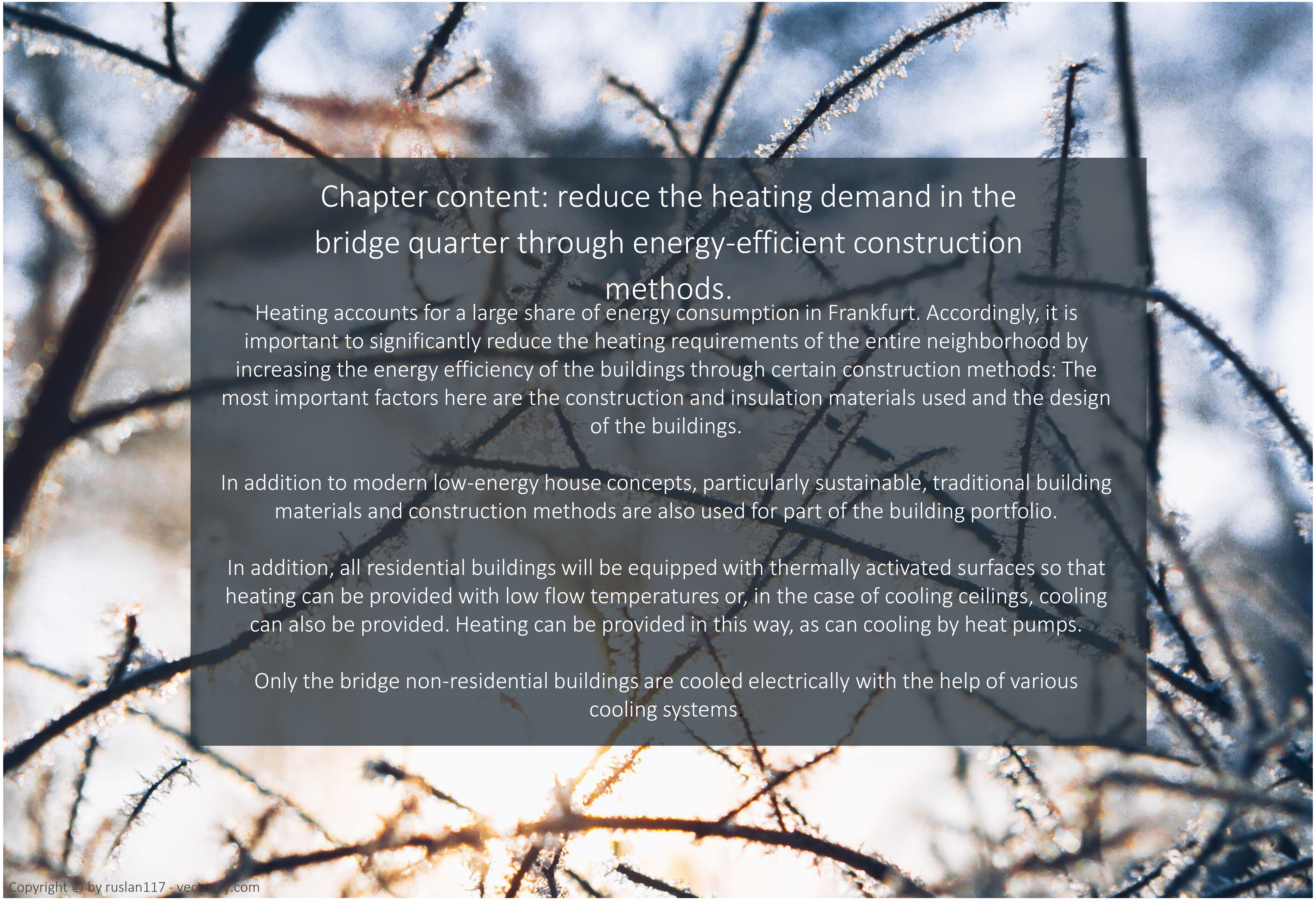
Heating and Cooling Demand of the Frankfurt Bridges

The Frankfurt bridges can also be self-sufficient in terms of heating and cooling consumption if they are built appropriately

The 1.15 million square meters of building space in the Bridge Quarter require around 40 GWh/a for heating. The 875,000 m2 residential building area accounts for around 26 GWh/a, as their optimized construction allows them to be designed like low-energy buildings with a heating energy requirement of less than 30 KWh/m2 a. The 275,000 m non-residential building area, on the other hand, requires a total of 14 GWh/a for heating. The 275,000 m2 of non-residential space, on the other hand, require a total of 14 GWh/a of heating energy, due to long opening hours and to compensate for heat losses caused by public traffic. For thermal cooling, 26 GWh/a of heat is taken from the entire bridge residential buildings and fed into the ground for regeneration. The non-residential buildings, on the other hand, use only electrically powered air conditioning.



Chapter content: reduce the heating demand in the bridge quarter through energy-efficient construction methods.

Heating accounts for a large share of energy consumption in Frankfurt. Accordingly, it is important to significantly reduce the heating requirements of the entire neighborhood by increasing the energy efficiency of the buildings through certain construction methods: The most important factors here are the construction and insulation materials used and the design of the buildings.

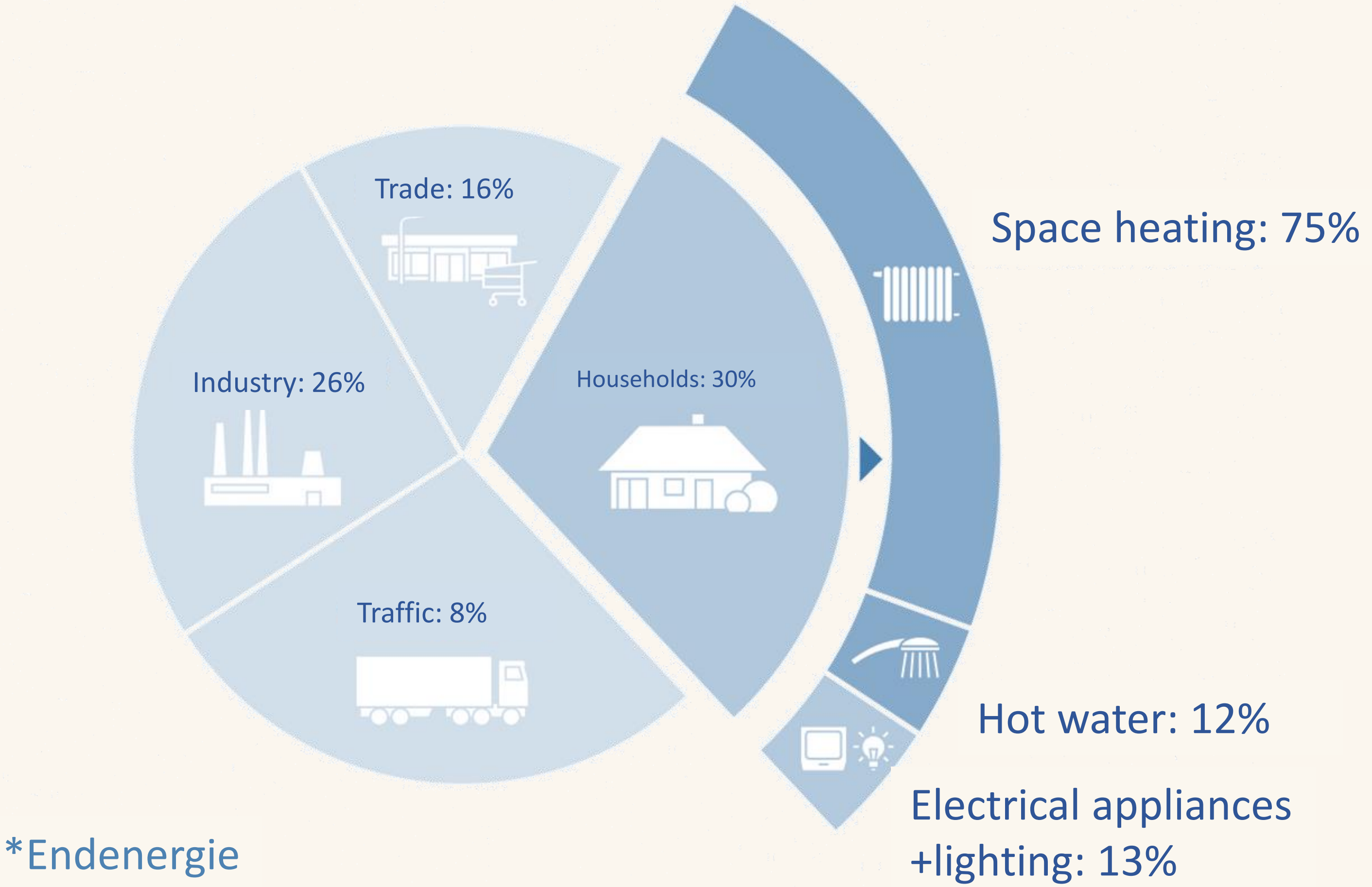
In addition to modern low-energy house concepts, particularly sustainable, traditional building materials and construction methods are also used for part of the building portfolio.

In addition, all residential buildings will be equipped with thermally activated surfaces so that heating can be provided with low flow temperatures or, in the case of cooling ceilings, cooling can also be provided. Heating can be provided in this way, as can cooling by heat pumps.

Only the bridge non-residential buildings are cooled electrically with the help of various cooling systems.

Household heating accounts for around a quarter of energy consumption in Germany

Accordingly, the Frankfurt Bridge neighborhood must be
As a "showcase of the future", massively reduce the energy required for heating (and cooling)



Quelle: dena / Energiedaten BMWi

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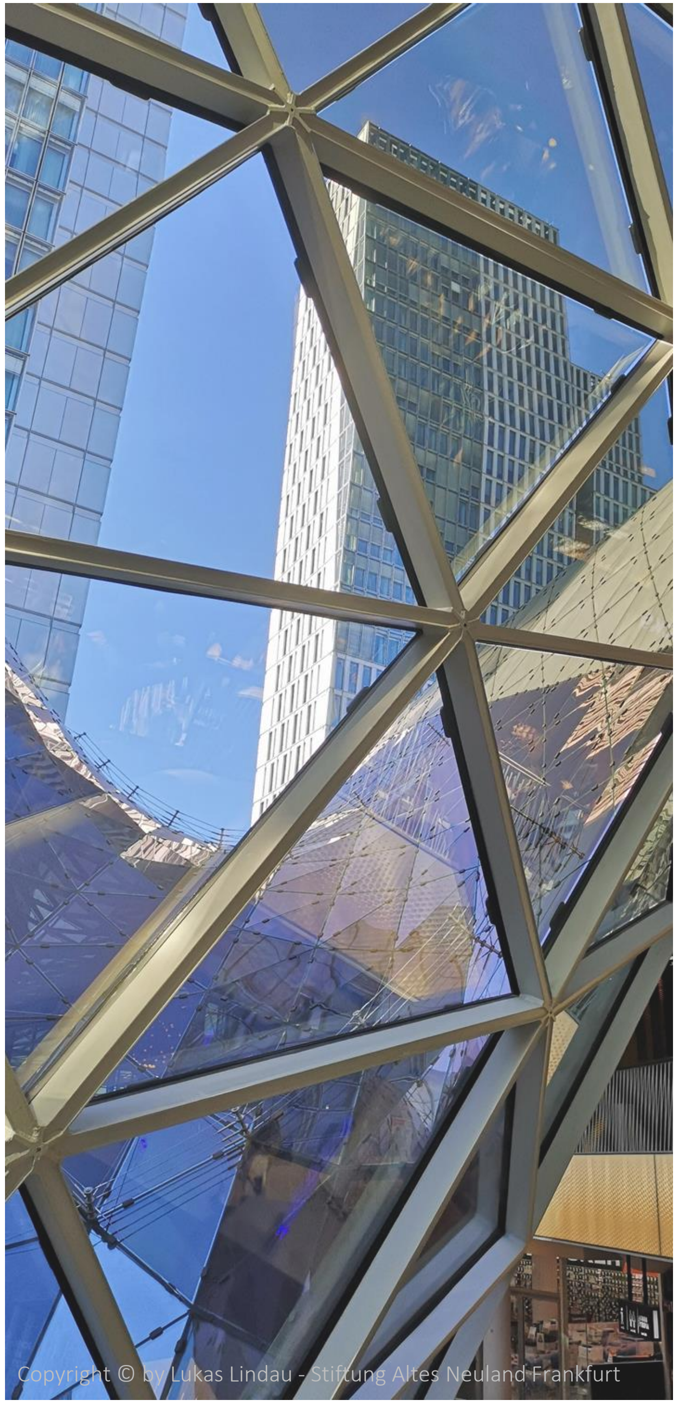

Whether old building or glass skyscraper: The energy efficiency of many existing buildings is "suboptimal" - to put it mildly

A look at the energy certificates shows: The average consumption per square meter in Frankfurt is still between 150 and 200 kWh/m²a. The EU Commission is aiming for around 30 kWh/m²a as the low-energy standard.

New buildings in Germany must not have more than a maximum of 55 kWh/m²a since 2020.

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The 875,000 m² bridge residential buildings as low-energy buildings require a total of approx. 26 GWh/a thermal energy for space heating

For all residential buildings on the bridges, the target value of the EU Commission of 30 kWh/m² a is undercut. This also complies with the Building Energy Act of 2021.

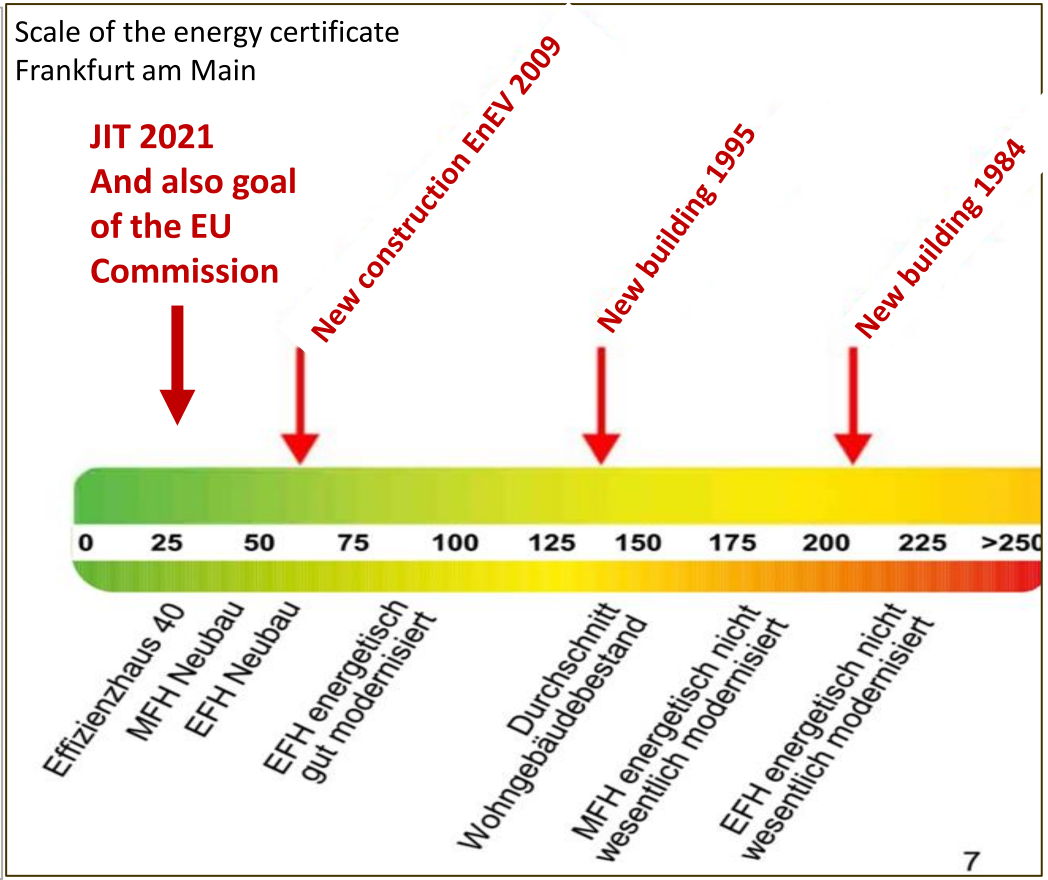
This is possible because heat pump technology is used and the construction and energy technology of the buildings are optimized.

Heat demand

Building category	Share (%)	Surface area (m)²	Spec. heat demand (kWh/m² a)	Total heat demand (GWh/a)
Residential	**76%**	**875.000**	**30**	**26**

Consumption in kilowatt hours (kWh)
Per m² and year

Building-area in m²	Energy source/ Heating system	Low	Medium	Increased	Too high
100 – 250	Natural gas	bis 89	bis 157	bis 244	ab 245
	Heating oil	bis 101	bis 162	bis 242	ab 243
	District heating	bis 80	bis 135	bis 236	ab 237
	Heat pump	bis 27	bis 43	bis 96	ab 97
	Wood pellets	bis 64	bis 131	bis 227	ab 228
251 – 500	Natural gas	bis 86	bis 150	bis 233	ab 234
	Heating oil	bis 98	bis 159	bis 239	ab 240
	District heating	bis 77	bis 128	bis 222	ab 223
	Heat pump	bis 25	bis 42	bis 94	ab 95
	Wood pellets	bis 60	bis 123	bis 215	ab 216



The residential buildings on the bridges have a heat demand of about 26 GWh/a, the heat demand for all non-residential buildings on Frankfurt bridges is 14 GWh/a in total

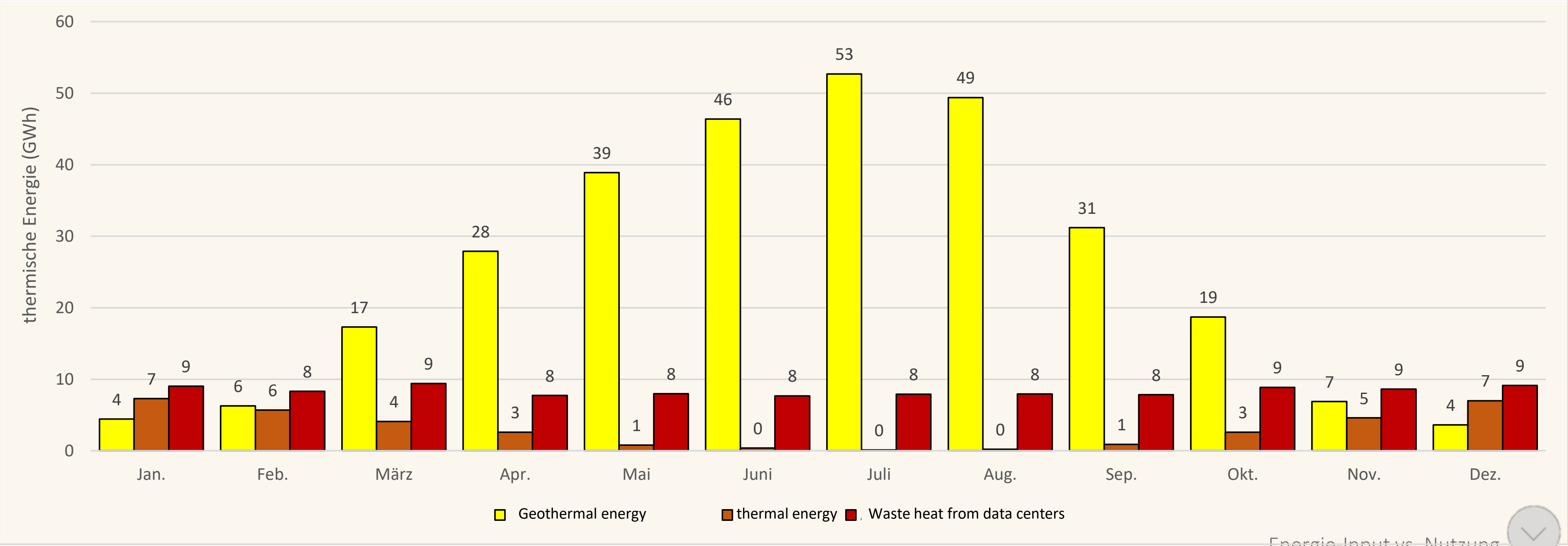
In the non-residential building stock of the bridge quarters, the specific heat demand has been calculated with the help of the "Announcement of the Rules for Energy Consumption Values" (BAnz AT 16.04.2021 B1) and with the help of comparative values from practice. In the calculations, it is assumed that the heat demand can be reduced to one third of the values stated in the announcement for already existing non-residential buildings. The specific heat demand for non-residential buildings changes with the building type. For the planned building types or usage distribution on the bridges, the total demand is about 14 GWh/a.

Heat demand

Building category	Share		Usable area (m)^2	spec. heat demand / cooling demand (kWh/m^2 a)	Heat demand (GWh)
Residential	76%				**26,2**
Residential buildings (heat demand for space heating)			873.257	30/30	26,2
Residential buildings (cooling demand for room cooling)			873.257	30/30	26,2
Non-residential	24%				**13,6**
Cafés, kiosks, teahouses, etc. Small restaurant		12%	33.001	92/	2,0
Restaurants, bistros		10%	27.501	92/	1,7
Grocery stores (small/large)		11%	30.251	57/	1,2
Special sales stores (art, organic flowers, etc.)		10%	27.501	55/	1,0
Micro-enterprises (repair café, cooking school)		4%	11.000	56/	0,4
Service providers (hairdresser, cosmetics, cobbler, etc.)		6%	16.501	45/	0,5
Medical practices of all kinds		5%	13.751	66/	0,6
Sports activity (fitness, dance, gymnastics, etc.)		4%	11.000	76/	0,6
Crèches/kindergartens/education		4%	11.000	58/	0,4
Primary/secondary schools		3%	8.250	58/	0,3
Music pavilion, hobby pop-up, theater, other. Culture		6%	16.501	69/	0,8
Special shelters (women's shelter, etc.)		2%	5.500	75/	0,3
Div. offices (landscapers etc. max. 5 employees)		1%	2.750	58/	0,1
Swimming pools with special focus (3 pieces)		3%	8.250	181/	1,0
IT College		10%	27.501	78/	1,4
Academy of Arts and Crafts		9%	24.751	78/	1,3

Almost 440 GWh/a of thermal energy is collected from three energy sources with the help of the Frankfurt bridges: Solar thermal energy, geothermal energy and waste heat from data centers - but only 40 GWh/a of heat is required on the bridges.

However, it must be taken into account: In the end, only 238 GWh/a of the 438 GWh/a of heat can actually be used: The rest is lost due to the losses typical for geothermal storage despite good insulation and short transport distances.



Energie-Input vs. Nutzung

Since only about 40 GWh/a are needed by the bridges themselves, almost 200 GWh/a of the 238 GWh/a heat from the ground remain. This must be extracted and used along the bridges in winter, as the ground otherwise heats up over time: In the distant future, the collected surplus energy will be used to supply the adjacent residential and non-residential buildings along the bridges - as soon as they can obtain their space heating from heat pumps. Until then, other consumer solutions will have to be found.

Storage of solar thermal energy in the ground is always accompanied by an efficiency of only 30% even with good insulation and short distances

Thermal source (GWh)

PVT (solar thermal)	303
Data centers (RZ)	100
Geothermal energy	35
(zuzügl. Wärmepumpen-Energie	*13)*
Total thermal input energy	**438**

Consumption (GWh)

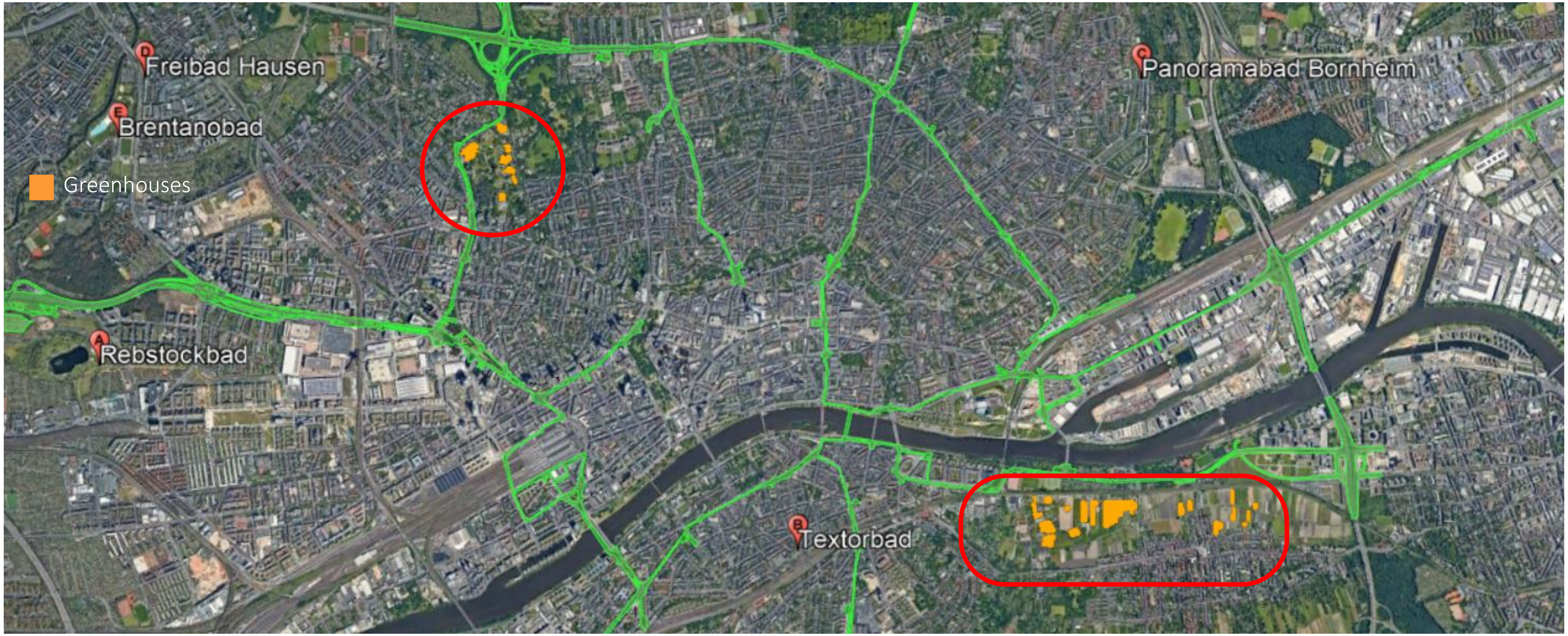
Direct consumption in winter	51
Saved in summer	252
Direct consumption in winter	50
Saved in summer	50
Residential	26
Non-residential	14
Greenhouses	20

Utilization (GWh)

Direct consumption PVT		51
Direct consumption RZ		50
Stored PVT heat	252	
Stored RZ heat	50	
Saved sum	302	
Of which usable after losses		102
Geothermal energy		35
Total usable thermal energy		**238**

Possible customers along the bridges can be swimming pools, for example, or greenhouses. There are a number of greenhouses in Frankfurt: one in the Palmengarten, the other in the Oberräder fields.

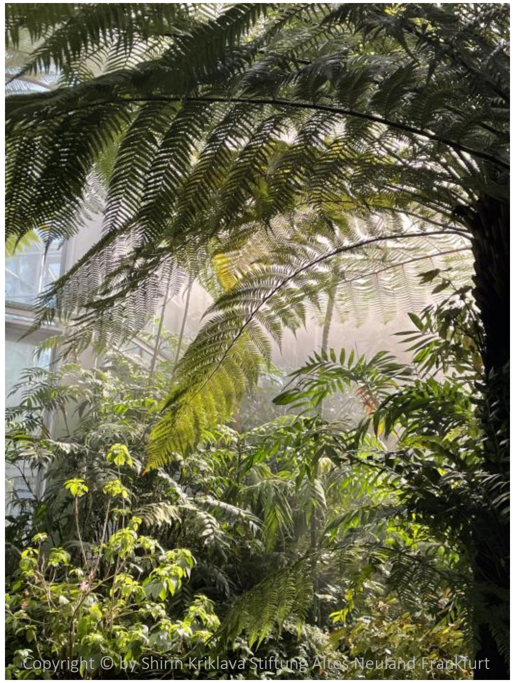
As soon as the building stock along the bridges is equipped with heat pumps and thermally activated surfaces, the Frankfurt bridges will be able to release their thermal energy to them. However, since the gas heating systems will only disappear after renovation and new construction cycles of 20 to 30 years, the surplus heat must be used elsewhere until then. If it were not withdrawn from the ground storage tanks in winter, the ground would heat up over the years, which would have negative consequences for the groundwater and possibly also for the geotechnical conditions.

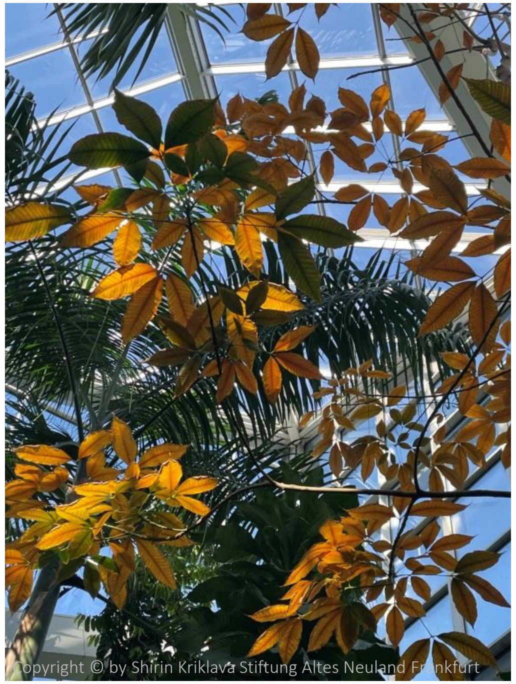


Around half of all greenhouses along the Frankfurt bridges can be heated in winter with thermal heat from the ground

Greenhouses with a total area estimated at 85,000 m^2 are located along the Frankfurt bridges. They consume significantly more heat per square meter in winter compared to residential or non-residential buildings. The average heat consumption for a greenhouse that needs to maintain an average temperature of at least (18 °C) in winter for tropical plants, for example, is over 400 kWh/m^2 a. Greenhouses with European plants, on the other hand, for which the temperature must not fall below only 5° to 10 ° in winter, require 60 to 120 kWh/m a. [2]

Greenhouses along the bridges can get half of their estimated heat demand of about 40 GWh/a from geothermal heat provided by the geothermally activated piles of the bridge columns; the other half of their demand can be met with the help of solar thermal PVT heat stored in the ground during summer BETS.





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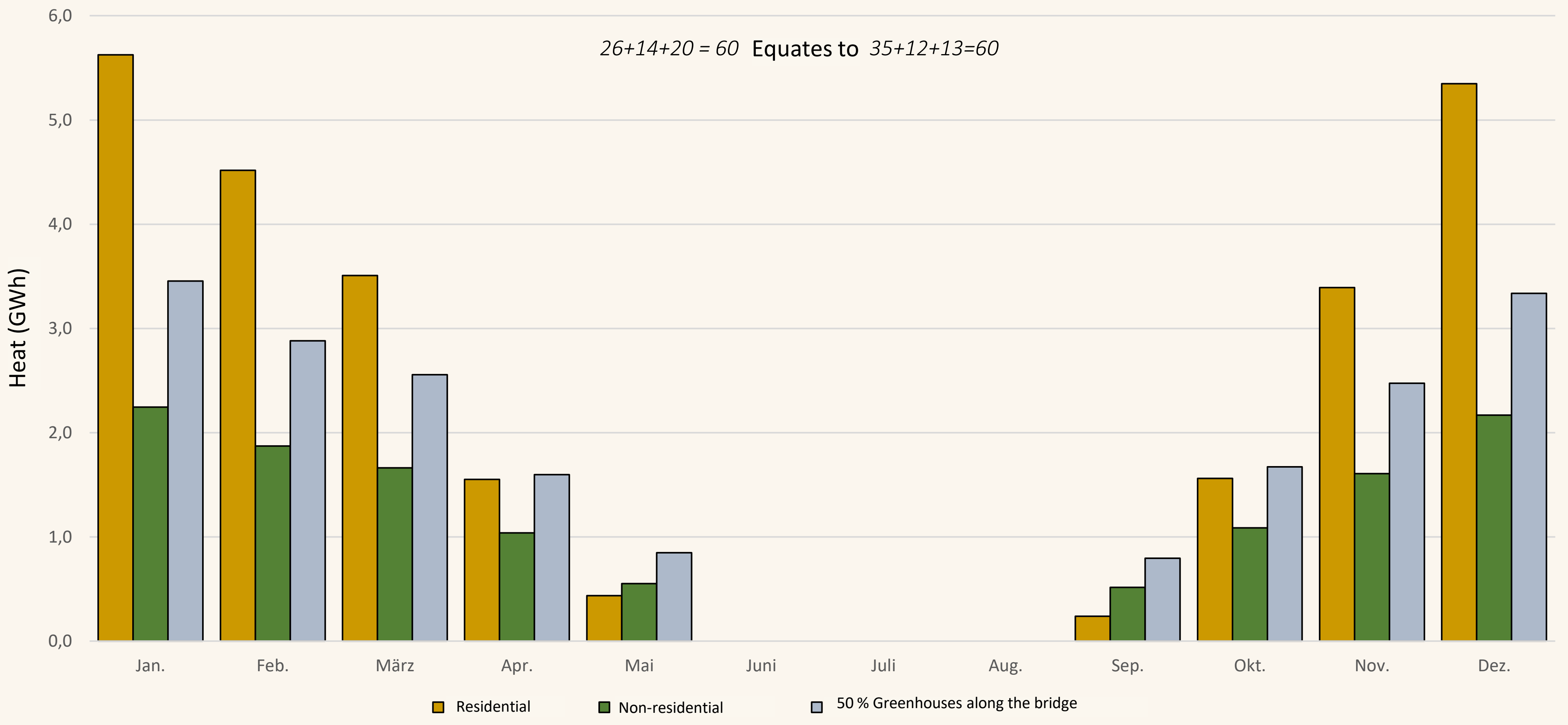
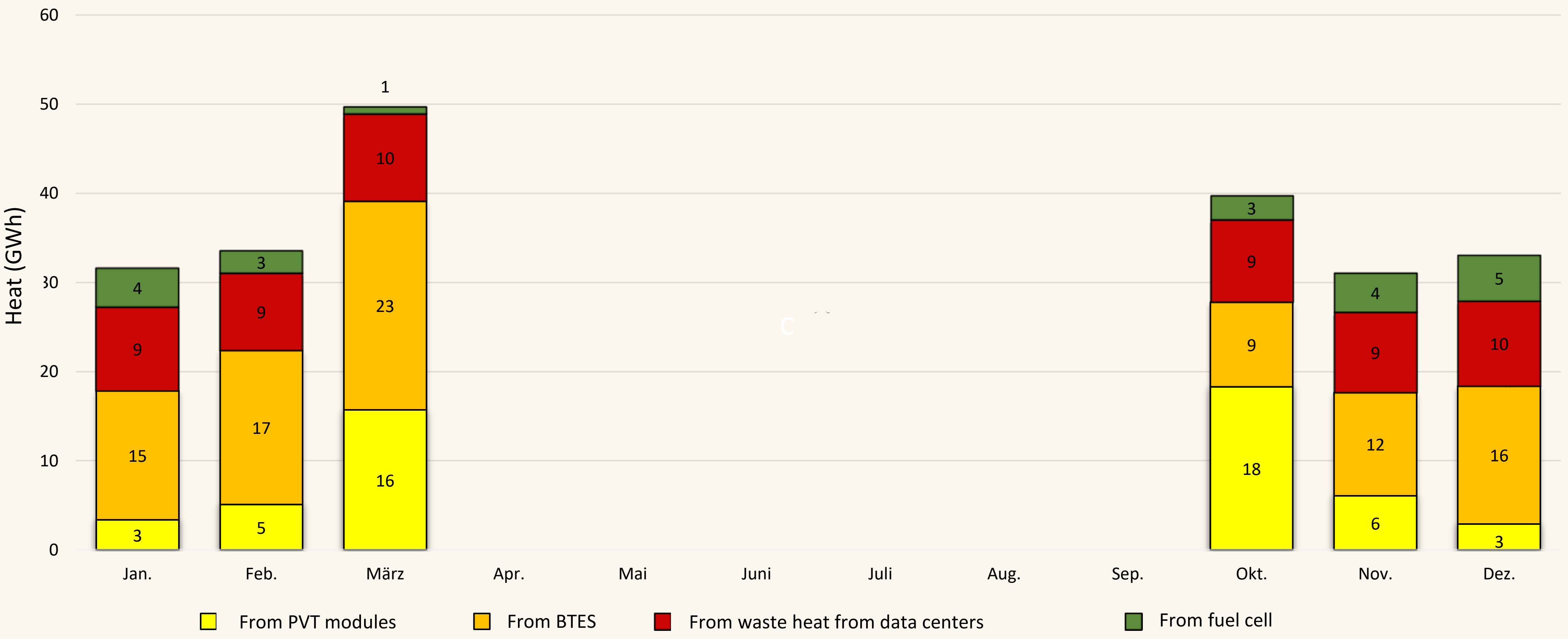
The space heating consumption on the bridges of 26 GWh/a by residential buildings and 14 GWh/a by non-residential buildings, and the consumption of half of the greenhouses along the bridges of about 20 GWh/a, can be met with the 35 GWh/a of geothermal energy and the 12 GWh/a of solar heat plus 13 GWh/a of heat pump energy



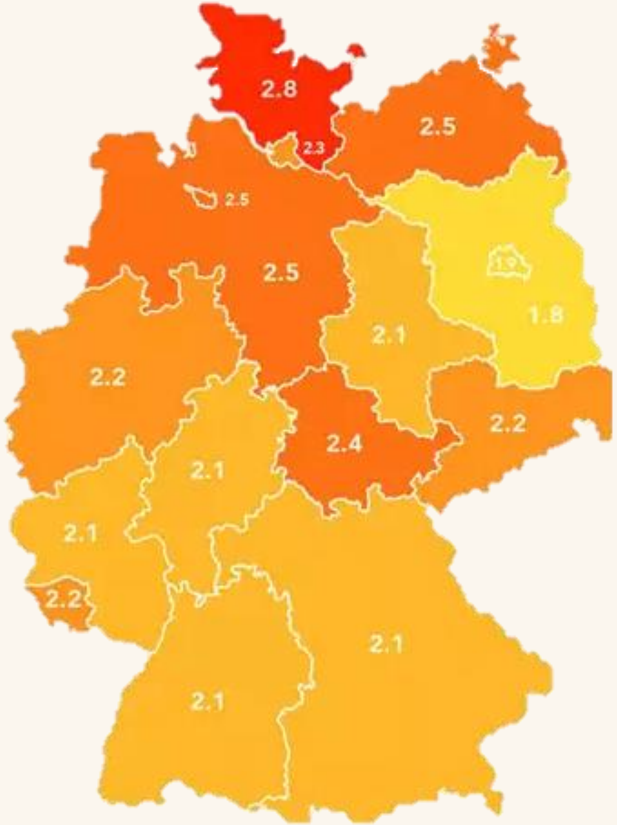
In addition to geothermal heat, about 220 GWh/a of heat from other sources is available in winter

This heat can be used to heat the other half of the greenhouses, whose heating needs are not met by geothermal energy. Defrosting roads or warming bus stops, on and under bridges where people have to wait, can also be potential consumers, as can swimming pools or large halls near bridges.

As soon as buildings along the bridges switch to heat pump heating, they will naturally receive priority heat from this large (albeit only low-temperature available) "heat stock".



Heat rise (°C) of households after 3 hours - with an indoor temperature of 20°C and an outdoor temperature of 30°C.



Study tabo. Basis >80,000 German households

Energy demand for air conditioning is growing in Germany

In Central Europe, and thus also in Germany, summers are getting hotter and hotter, and the air-conditioning requirements are getting higher and higher, while people's expectations of comfort remain the same.

The buildings on the bridges are partly shaded by taller buildings along the bridges or by the trees that line the bridge like a treetop walkway; but in order to cope with the changed climatic situation in the long term, they will be equipped with cooling ceilings in the roof floors.

Chilled ceilings are -just like underfloor heating- thermally activated surfaces. The only difference is that they receive cool fluid from the heat pump and return heated fluid.

Federal Statistical Office 2020

In order to be able to cool optimally and energy-efficiently, thermal optimization must already be provided for structurally when planning the buildings on the bridges - just as is the case for heating.

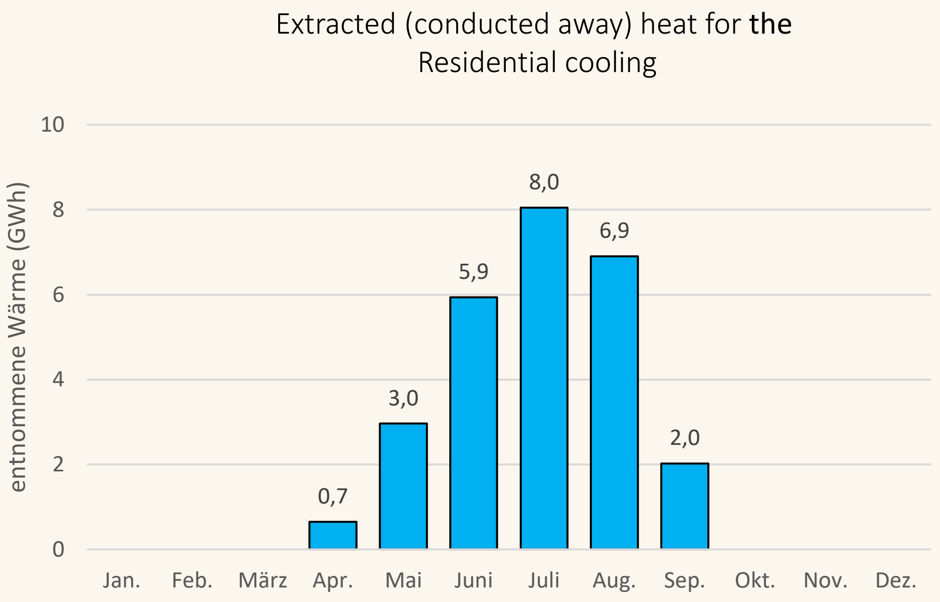
The energy expenditure for air conditioning systems

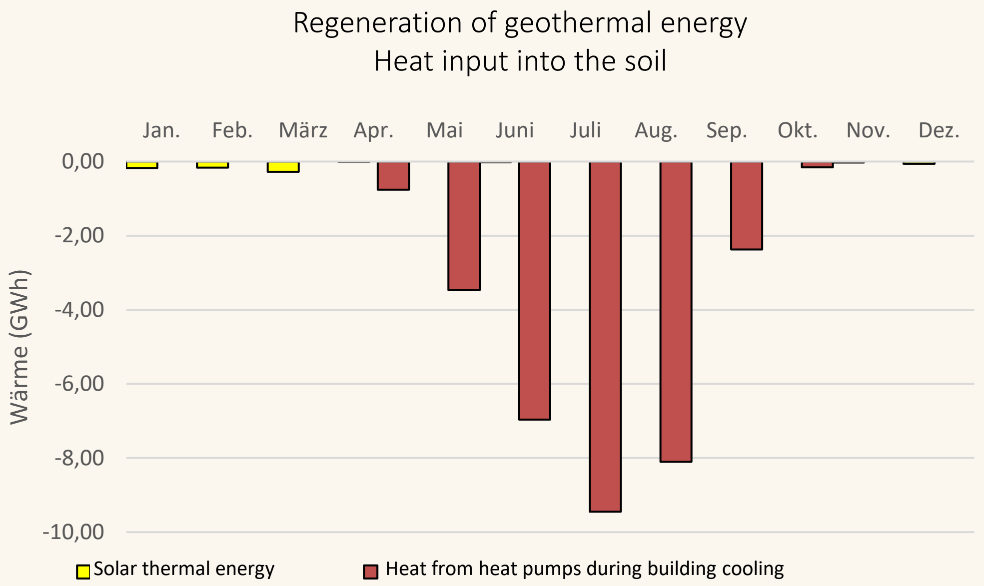
Even if the summer of 2021 in Germany seemed comparatively cold and wet, the coming years suggest increasingly hot summers in Central Europe.

On the Frankfurt bridges, the heat pumps not only solve the heating problem, but also the air conditioning problem:
The heat energy of the residential buildings is pumped down into the ground via a brine that flows in the thermally activated ceilings through the ground-level geothermal system. There, the fluid releases its thermal energy to the colder ground, and thus comes back up cooled to absorb energy again and transport it down. For thermal cooling of the residential buildings, 26 GWh/a of heat have been taken from the residential buildings.

The cooling of the residential buildings simultaneously serves the regeneration of geothermal energy

To provide space heating for the bridge buildings, heat must be extracted from the ground in winter. To prevent the earth from cooling down over the years, the heat extracted in winter must be "regenerated". This is realized mainly in midsummer with the help of thermal energy sent down into the ground from the buildings for cooling purposes.





If heat were only ever extracted from the earth without sending new heat down, it would cool down over time and could no longer be used for heating in winter. On the Frankfurt bridges, however, about 26 GWh/a of heat is extracted from residential buildings in the course of cooling buildings in summer and sent underground by means of heat pumps for the purpose of regeneration.

The buildings on the Frankfurt bridges will achieve very low thermal energy consumption

On the residential buildings of the bridges, the EU target of 30 kWh/m^2 a will be met. Several factors affect this value, but the most important are:

Construction

- Construction type: single-family house vs. multi-family house, compact construction vs. dissected construction, row house vs. detached building
- Building physics: building materials (brick, concrete, wood, clay, etc.) and insulation materials

Power Engineering

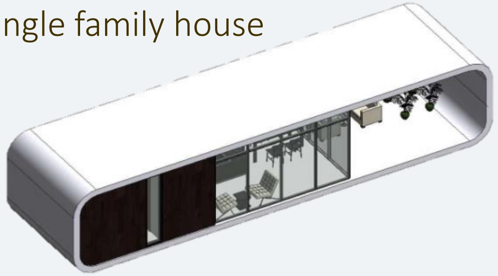
- Energy source: gas, oil, pellets, (air) heat pump
- Sealing: especially windows and doors
- Utilization of exhaust air heat/cooling

On the Frankfurt bridges there are manifold construction methods with different construction and insulation materials.

The energy sources used are heat pumps, supported by ground-source geothermal energy, and electricity for heating water.

Energy consumption is optimized by appropriate seals, in parts by the (filter-free) thermal use of exhaust air, and by appropriate control systems.

Single family house



Small apartment house

Terraced houses

From an energy point of view, terraced houses are the best, because there is less external surface per square meter of building area, through which heat could be emitted

Single-story single-family houses are the most unfavorable from an energy point of view.

Since the bridges in the inner city area are only sparsely populated with comparatively low buildings, the buildings that are particularly good in terms of energy are mainly found on the outer arms: About 450 of the approximately 2,200 buildings are single-story and freestanding (some of them with extended roofs). With well thought-out insulation concepts, however, even these can be designed to be very energy-efficient compared with existing buildings.

Another 950 buildings have two or two and a half floors. About 600 buildings have three or three and a half floors. And only 190 buildings have 4 floors or more.

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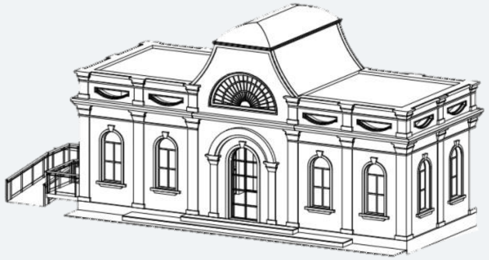
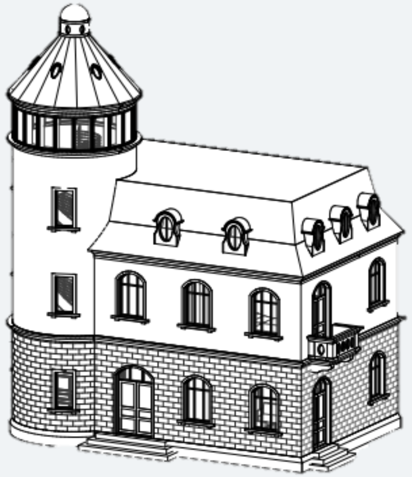
Art Nouveau family house



Apartment house old building with dissecting? Curvature



Old building row houses compact

About half of all buildings on the bridges are in the old building style and are challenging due to their building curvature

Whether Art Nouveau or Wilhelminian style, a multitude of turrets, oriels, balconies and pinnacles dissect the surface of a building, creating more surface area for heat dissipation.

If one does not want to do without a bay window for reading or a work tower room with a view, more compensatory measures must be taken.

Compact buildings in the old building style, on the other hand, which are built in rows, achieve almost as good energy values as their counterparts in the modern row house style - not least due to their large windows when these face south.

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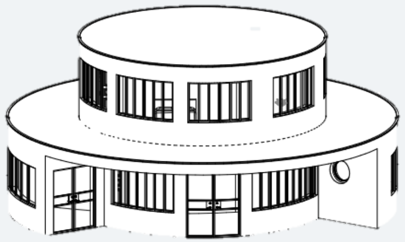
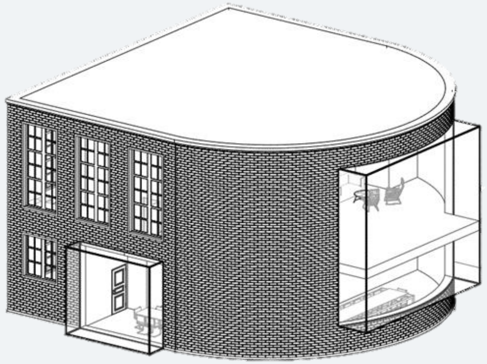
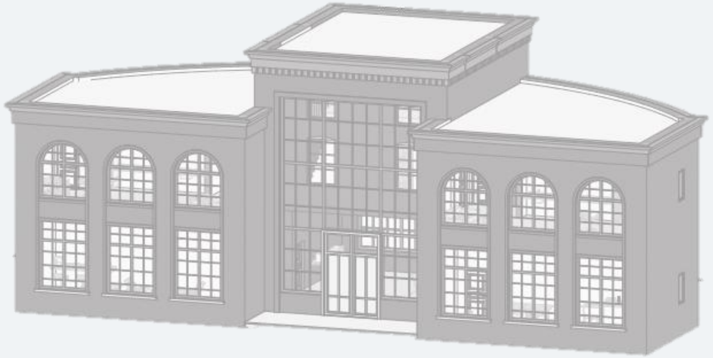
Bauhaus style family house



Single family house with glass cubes



Apartment house - loft



Curves and high ceilings are also not conducive to maximum energy efficiency

However, very good values can be achieved even in such buildings if all other possibilities for savings are used.

It would not be helpful to build only rectangular boxes in long rows for the sake of maximum energy efficiency. Buildings should be designed in such a way that people enjoy living, working or meeting for meals and other activities.

The buildings on the Frankfurt bridges also achieve the energy standards required by the EU with their extravagant architecture, which is intended to create humane housing and living space for people.

The degree of compactness is determined by building curvature as well as by row versus single development

Style # Floors	Old building	Early modernity (Loft, Bauhaus, etc.)	Modern
1	70%	5%	%25
1,5	70%	5%	%25
2	50%	10%	40%
2,5	50%	35%	15%
3	40%	40%	20%
3,5	20%	50%	30%
4	20%	50%	30%
> 4,5	10%	70%	20%
	Low degree of compactness	Very compact	Medium compact

Rough breakdown of the approximately 2,200 buildings on the Frankfurt bridges

It will only be possible to determine precisely which buildings in the individual neighborhood sections have which style and thus thermally relevant design during the preliminary planning phase, which will take several years.

On the Frankfurt bridges, both are innovatively combined: humane beautiful architecture with optimized energy efficiency

Bodo Wartke - Architecture in Germany. 3min 46
https://www.youtube.com/watch?v=9yRZkYZiM88

Monotonous architecture depresses, while beautiful, successful architecture is loved by people: it has a comforting and cheering effect - almost everyone has experienced this.

Innovative energy technology makes it possible to realize the full range of housing options on Frankfurt's bridges that different groups of people prefer: whether old buildings or modern architecture - everything is designed to be energy-efficient and humane.

In addition to the type of construction, the building materials used play a major role in the energy consumption of buildings

There are four criteria for construction materials to be used on the Frankfurt bridges:

1. They must have good insulating properties
2. They must be sustainable, taking into account the entire ecological rucksack
3. They must not present a fire hazard or increase the risk of fire
4. They must be comparatively light because of the statics of the bridges

Each building material has its strengths in a combination of the four filter criteria, and therefore completely different materials are also used on the bridges, true to the concept of providing a showcase of innovations.

Some of these are conventional, tried-and-tested building materials and construction methods (e.g. timber framework), while others are modern, innovative building materials (e.g. Rabbitz constructions made of round iron, wire mesh and lime plaster as well as lime-cement plaster).

Which materials are used where is decided section by section, according to the architectural style in the respective section (for example, it does not make sense to want to build ultra-modern spherical buildings from classic half-timbering) and also with regard to the locality. The design of the bridge itself per section is also a determining factor in the selection of the building material: if the bridge is founded by more columns at one point, for example, a building above it can sometimes be made of tuff - although this is heavier as natural stone than, for example, timber framing, it is still comparatively light, very easy to work with craftsmanship, ecologically sound and does not burn.

Various types of "aerated concrete" are one of the most important groups of building materials for the buildings on the Frankfurt bridges due to their lightness, good designability and thermal insulation properties without additional thermal insulation measures

Aerated concrete belongs to the group of lightweight concretes, even though, strictly speaking, it is not concrete at all, since it does not contain aggregates.

Autoclaved aerated concrete has excellent thermal insulation properties due to the many air chambers inside. Therefore, aerated concrete can be used to build exterior walls that meet the low-energy house standard without additional thermal insulation measures.

It is just perfect for the decoration of the most diverse architectural styles and especially for the processing by artisans.

The relatively low density only has a disadvantageous effect on the sound insulation properties, and the moisture compensation behavior is comparatively poor due to the many pores.

However, there are already numerous innovative solutions for the disadvantages in terms of sound insulation - or even moisture protection - so that autoclaved aerated concrete is a suitable material for the Frankfurt bridges in its most diverse variants, especially for the neighborhood sections in the old building style.

However, the Frankfurt bridges also rely on traditional sustainable building materials

Wood and clay are both sustainable, comparatively lightweight in certain designs, insulate well, and (with proper treatment) are flame retardant. Without complementary materials for insulation or structural improvement, neither material can reach its optimum. On the Frankfurt bridges, the aim was to implement a wide variety of construction methods and combinations of conventional and sustainable building materials in their buildings - depending on the architectural style in a section of the quarter, a different construction method would then prevail. Accompanied by research and science, the best construction methods in terms of CO_2 emissions and sustainability are to be identified over the years. For example, the bridge section above the Deutsche Bank Arena parking lot in the south of Frankfurt is suitable for half-timbered houses, where a homage to Frankfurt's old town is being created on an area of 27,000 m² . Some of the houses in Frankfurt's old town were masterpieces of half-timbered architecture, which can still offer an excellent living atmosphere today.

Learning from traditional buildings: the Pisé House in Weilburg made of rammed earth

Almost one third of humanity lives in earthen buildings - but these are usually only one or two stories high.

In Germany in the town of Weilburg stands the tallest house made of rammed earth, the five-story "Pisé House" built in 1828.

In the absence of wood and natural stone, several buildings of this type were built in the area at that time: an architectural art that has now fallen into oblivion and is worth exploring. Because the houses are still habitable today - the Pisé House, for example, has just been renovated as an apartment building.

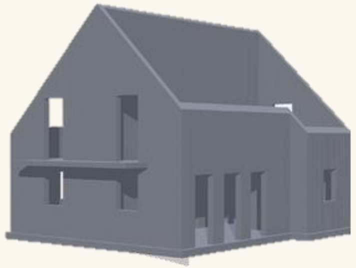
Further new territory: so-called rabbit constructions consisting of round iron, wire mesh girders, a plaster base and lime gypsum on the inside and lime cement plaster on the outside.

Rabbit structures are ideal for buildings on the bridges because their main building material, gypsum, is a multi-talent: as a purely natural product, it contains no pollutants, is associated with low CO_2 emissions, and can also be recycled indefinitely. In addition, gypsum is not flammable thanks to the enclosed water and even has a fire-retardant effect. Due to its low thermal conductivity, gypsum retains heat for a long time - a big plus when it comes to heating. Its porous surface absorbs moisture well and can thus regulate the indoor climate.

There is only one drawback: gypsum is partially soluble in water. Therefore, in the interior use lime gypsum, and in the exterior - lime-cement plaster. In between there is room for insulation, which can be made of various materials (grass, hemp, etc., or even perlite).

The necessary U-values* for the goal of getting below 30 kWh/m^2 a heating energy can be achieved with the right combination of building materials and construction technology with the materials presented here

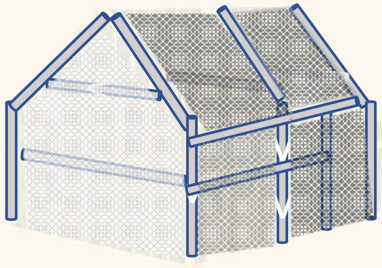
The Frankfurt bridges are also a showcase of innovations in terms of modern building physics, so that a wide variety of building materials, combinations and insulation systems can be tried out and further researched in long-term tests.


(Porous) concrete


Wood (frame construction)

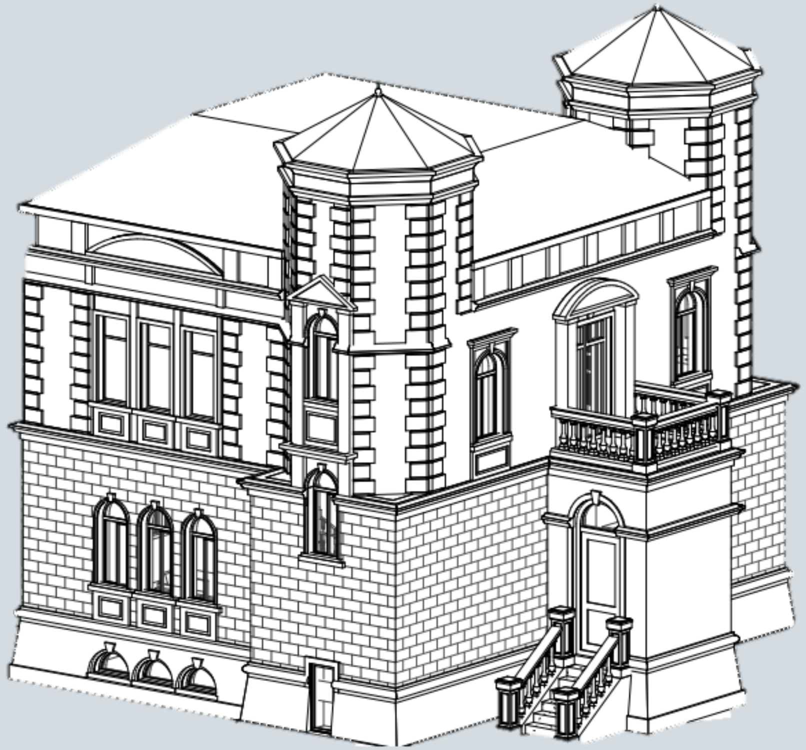

Brick / natural stone masonry

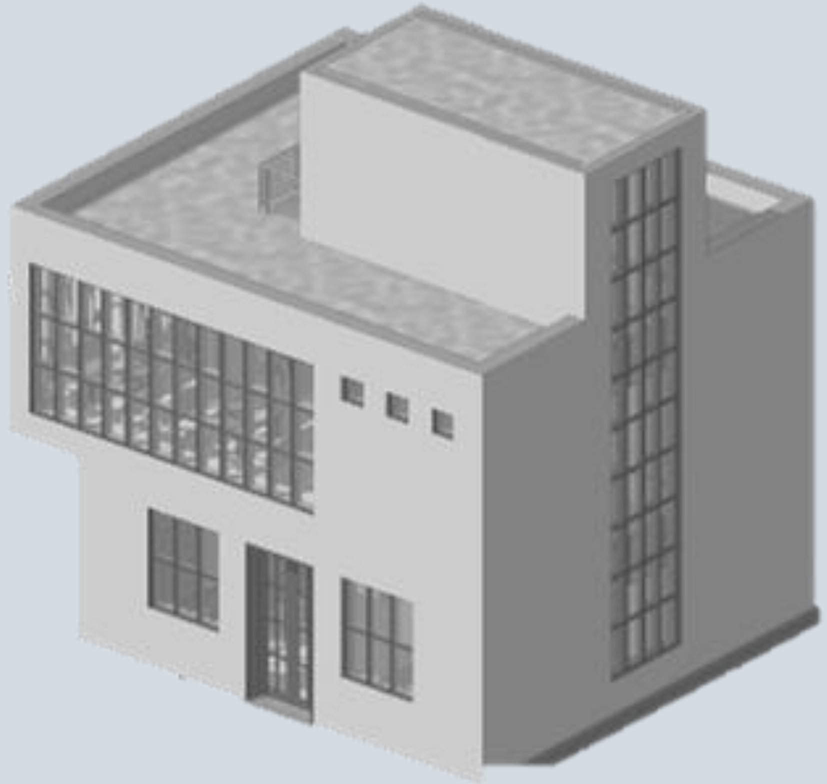

Rammed clay


Rabbitz construction

* Heat transfer coefficient

Sample calculation for two buildings from the Brücken building portfolio: Without optimization, the U-values were over 100 kWh/m^2 a - with optimization, both buildings were in the range of low-energy houses





All buildings on the bridges are heated with heat pump technology

No matter what type of construction and building material: The decision whether to heat with oil and gas or with a heat pump system has the greatest impact on the EU target of 30 kWh/m^2 a for residential buildings

Conventional heating processes work by burning something, be it oil, gas or even pellets.

Against the background of CO_2 reduction measures, the heat pump has now become the means of choice: Here, nothing is burned, but a principle is used that works virtually the other way around like a refrigerator.

The heat pump uses a small amount of electrical energy and 75% of thermal energy (in the case of COP=4) from the environment, e.g. air, earth or brine from solar systems.

Compression processes are used to raise an environmentally friendly refrigerant to a higher temperature level so that it can be used to heat the water in the heating pipes.

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On the Frankfurt bridges, all buildings are equipped with thermally activated surfaces

Whether wall, floor or ledge in front of the window, the heating systems also have small disadvantages: With the wall, you have to know where heating loops are inside so as not to accidentally hammer nails into them; floor heating systems are comparatively sluggish: After all, you do not want to start heating already at noon, when you come home only in the evening at 20:00. And baseboard heaters, from which warm air blows, can also raise an unpleasant amount of dust, similar to air conditioners, and are a problem for allergy sufferers and asthmatics in particular.

In order to compensate for the negative effects of these modern and climate-friendly technologies on luxury, small conventional radiators that run on high-temperature heat (e.g. generated with fuel cells) are also installed redundantly in the buildings in isolated cases. These radiators are only used in special situations, for example, when heat is only needed for one or two hours in the evening during the transitional period and the underfloor heating, once started, reacts slowly and takes far too long to reheat; or as a backup in the event of a strong heat demand on a cold winter's day.

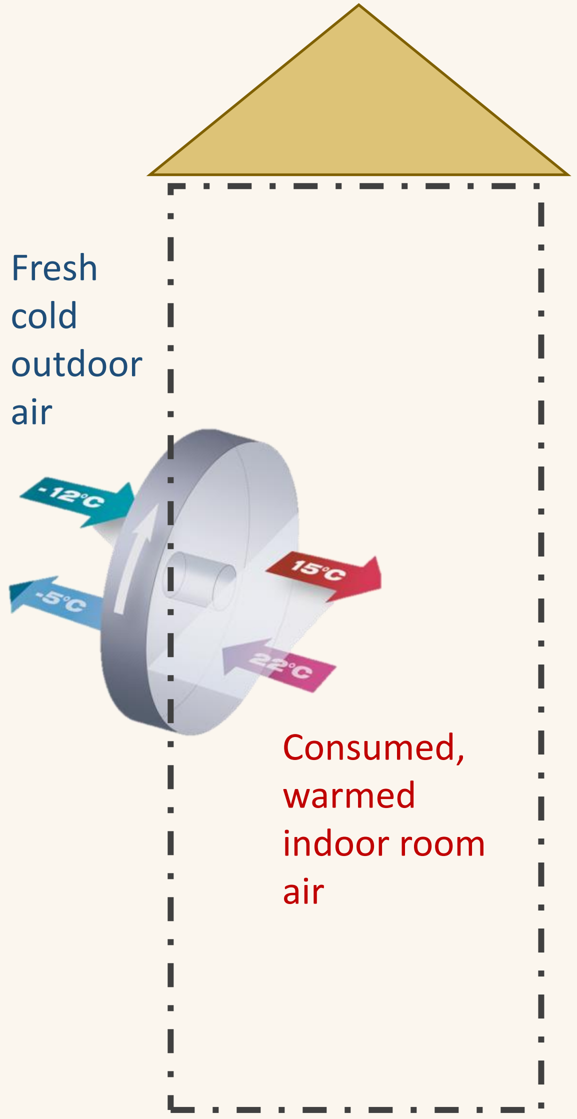
Other measures: Sealing and use of exhaust air heat of a building.

The fact that well-sealed windows and doors, including patio and balcony doors, help to save heating energy is generally known and has been common practice for years, even in new buildings.

Much less known and also less popular is the use of exhaust air heat from the rooms to preheat the incoming air in advance. The principle is simple: you want to get rid of stale, stuffy, heated air, but to do this, do not push open the windows, but suck the air and direct it outside in a pipe. Inside this pipe is a second pipe through which the fresh, but significantly cooler air flows in. This is preheated by the warm exhaust air before underfloor and wall heating do the rest.

The only drawback is that it is a system in which incoming air is passed through a filter system. And air flows from filtering systems are usually not pleasant - at least for living rooms.

There is a solution for this that does not use filters, but is made entirely of metal or ceramic and is easy to clean: the so-called rotary heat exchanger, although it should be noted that the term "exchanger" is somewhat fuzzy in terms of heat technology. This is because there is no exchange, only a one-sided transfer of energy. However, the result is clear: less energy is needed to heat a room with it.



The air only flows past metal or ceramics, so there are no filter membranes in between that could be breeding grounds for germs etc.

The rotor is driven by a small motor. One half of the rotor faces the interior, i.e. in the exhaust air stream, and the other side faces the exterior, i.e. the supply air stream.

The rotary heat exchanger is used to transfer heat from the warm exhaust air to the cold supply air. For this purpose, exhaust and supply air flow through the same cylindrical, rotatable metal structure with a time lag: the exhaust air heats up the metal structure in the cylinder and cools down itself. The roller rotates slowly in a circle so that the heated part comes into contact with the cold outside air, releasing the heat to the supply air. At the same time, the metal structure in the roll structure cools down to be heated up again later by the warm exhaust air.

The efficiency of this technology is up to 85%. This means that the warm air flowing away from the room manages to give up to 85% of its heat to the fresh air flowing in. You only need to reheat a little to get to 100%.

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Conclusion: Construction methods, building materials and energy technology on the Frankfurt bridges are geared to saving energy in heating and cooling

True to the motto of being "a showcase of innovations", sustainable building materials such as wood, clay or Rabbitz constructions are used on the bridges.

For each sub-quarter of the Frankfurt Bridges, it is necessary to examine in detail which building materials are most suitable for which building forms.

The energy technology, on the other hand, is equally modern and innovative for all 2,200 buildings: For heating and cooling, it is optimized by coupling with ground-level geothermal energy. So that this can also be used, all buildings are equipped with thermally activated surfaces.

By combining many consumption-reducing measures directly during the construction of the bridges and buildings, all bridge houses meet modern low-energy requirements.

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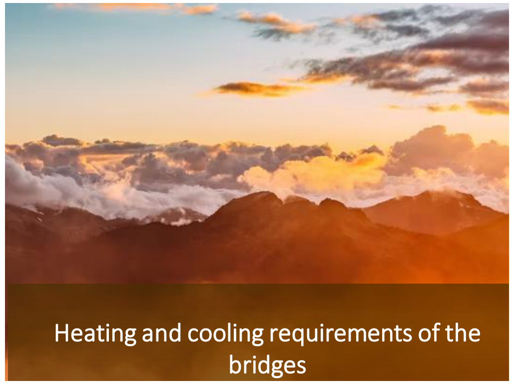
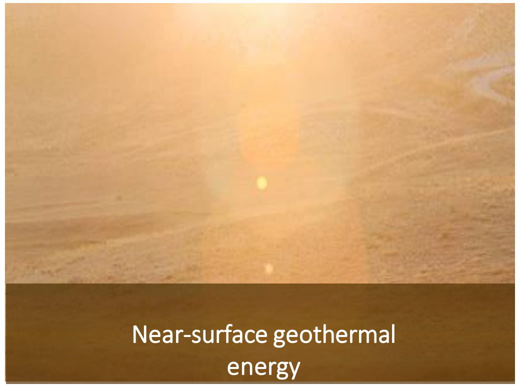
Electricity demand on the Frankfurt bridges


Photovoltaics as quarter power


Heating and cooling requirements of the bridges


Near-surface geothermal energy


The energy infrastructure of the future


The bridge world


Sustainability through technology


The Co2 balance of bridges

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Photovoltaics as Quarter Power

Unnoticed, Frankfurt's bridges are a huge power generator and an inner-city second power grid also for PV generation along their course: thus enabling the generation of over 415 GWh per year

The bridges can generate 140 GWh/a of electricity per year through the use of aesthetically pleasing or invisible photovoltaics in the downtown area and efficiency-maximizing photovoltaics on the outer arms.

If existing large parking lots of companies and institutions along the bridges are roofed over and equipped with photovoltaics, another 135 GWh/a can be produced. If the roofs of these companies and institutions are also covered with non-installed, roof-skin-friendly solar modules, an additional 142 GWh/a can be generated. With the help of the Frankfurt bridges, this electricity can be collected and transported to consumers or storage locations along the bridges.

By comparison, Frankfurt households consume 900 GWh per year.

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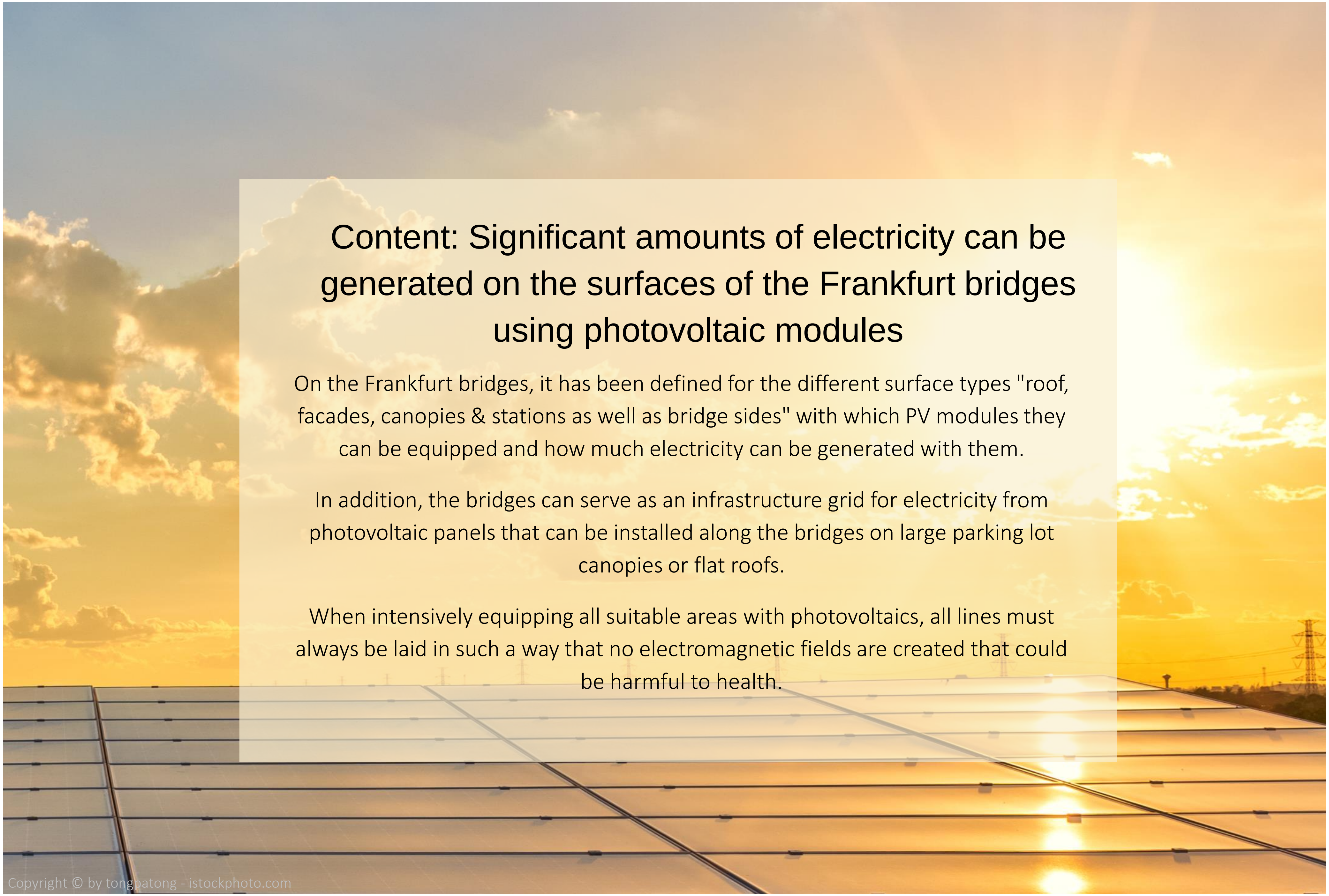


Content: Significant amounts of electricity can be generated on the surfaces of the Frankfurt bridges using photovoltaic modules

On the Frankfurt bridges, it has been defined for the different surface types "roof, facades, canopies & stations as well as bridge sides" with which PV modules they can be equipped and how much electricity can be generated with them.

In addition, the bridges can serve as an infrastructure grid for electricity from photovoltaic panels that can be installed along the bridges on large parking lot canopies or flat roofs.

When intensively equipping all suitable areas with photovoltaics, all lines must always be laid in such a way that no electromagnetic fields are created that could be harmful to health.

Frankfurt needs much more photovoltaic area

Less than 1 percent of the electricity in Frankfurt is currently produced by photovoltaics. Since the energy turnaround, the German government has envisaged covering 80% of Germany's electricity requirements from renewable energies by 2050. For Frankfurt, with its total electricity consumption of around 7,100 GWh/a, this means that around 5,700 GWh/a must come from renewable energies. And since wind cannot be expanded in Frankfurt because of the airport, photovoltaics will have to make the most important contribution.

Share of local electricity generation in electricity consumption (incl. Electricity for heat and mobility)

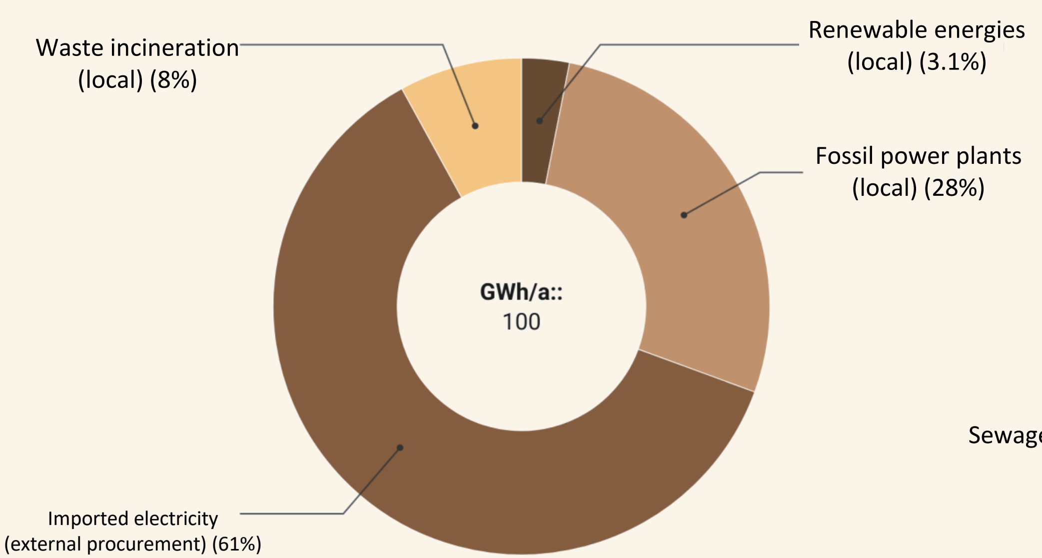


Chart: Altes Neuland Frankfurt • Source: Regionalgebiet FrankfurtRheinMain • Created with Datawrapper

Local power generation from renewable energies

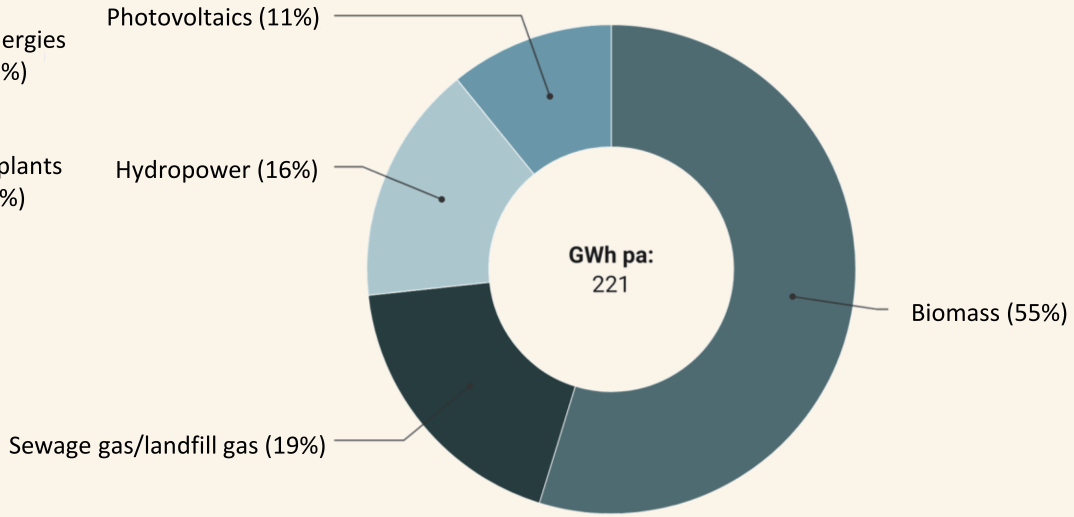


Chart: Altes Neuland Frankfurt • Source: Regionalgebiet FrankfurtRheinMain • Created with Datawrapper

Why isn't more photovoltaics being installed at the moment?

On the one hand, it should not be underestimated that our power grids were not originally designed to collect and transmit decentralized and highly volatile surplus electricity. However, while control systems for this purpose are being further developed and expanded, property owners, particularly in inner-city locations, are not yet following suit to the same extent.

For one thing, homeowners in existing buildings balk at the expense of tinkering with a working, leak-proof roof or running new lines through rented space.

In addition, the power supply from the central utility Mainova is cheap, convenient and already connected. The interplay between self-use of self-generated electricity and feeding the surplus into the utility grid also represents an additional effort for many homeowners in terms of control technology.

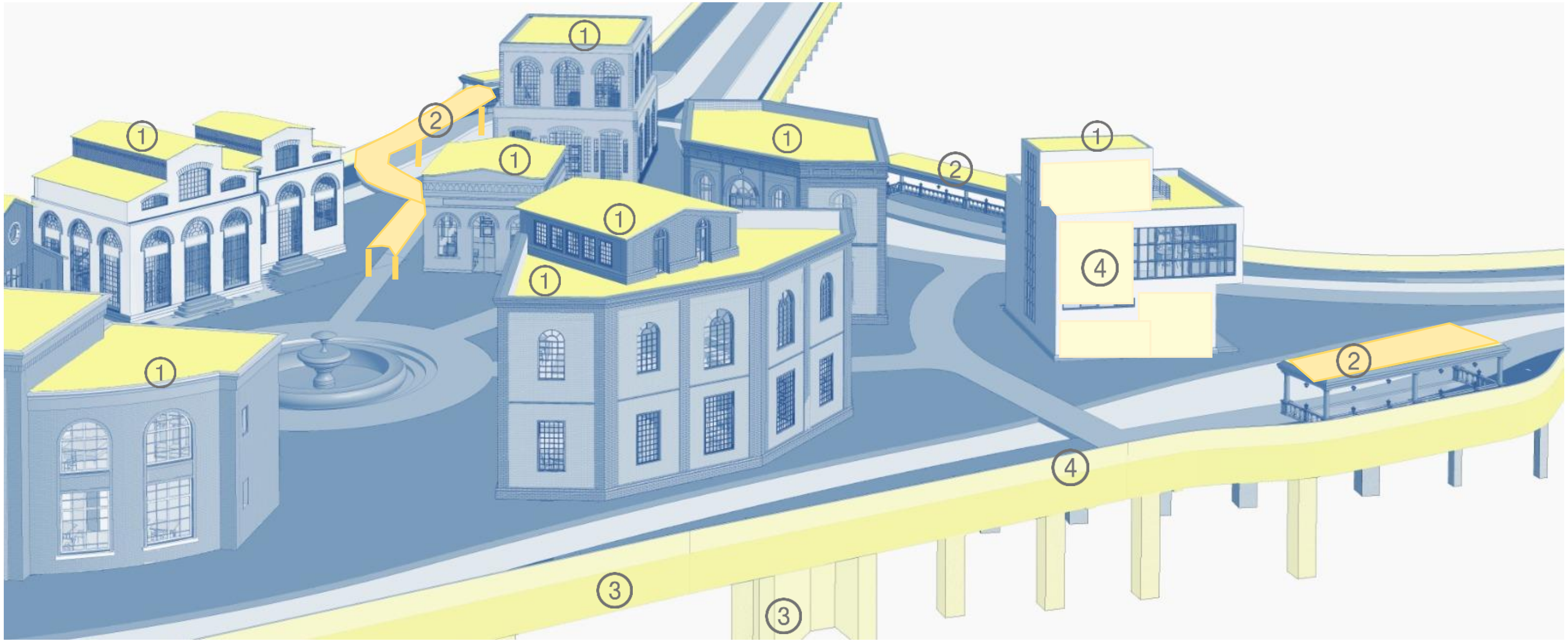
And another important knockout criterion for many building owners: photovoltaic systems usually do not change the appearance of a building in its favor, since they are classically developed primarily with efficiency in mind, not beauty.

On the bridges, all this is to change: everywhere where citizens can see the surfaces, aesthetically pleasing or inconspicuous photovoltaics will be installed. On the outer arms of the bridges, on the other hand, where hardly anyone looks at them from the side or above, much more efficient and visually less attractive photovoltaics will be used.

On the bridges, there is also no individual billing per building with the supplier Mainova, but there is an internal "netting" within the quarter, and a balancing with Mainova only takes place via internal supply nodes, the "supply centers".

Roofs, facades, walls, stations - on the Frankfurt bridges can be installed on many surfaces aesthetically beautiful photovoltaic modules from the pipeline of research and industrial development

There are different types of areas for mounting photovoltaic. The most important are: (1) building roofs, (2) roofs of stations or canopies over pathways, and (3) the sides of the bridge body along with the columns. PV modules can also be mounted vertically (4), e.g., on the guardrails or privacy screens at the edge of the bridge as well as on facades.
But they all have one thing in common: All photovoltaic modules should blend aesthetically into the cityscape or the "bridge image" in everyday life and not be particularly conspicuous.



On the Frankfurt bridges, a total of 1 million square meters of surface can be equipped with photovoltaics: 475,000 m^2 of roof surface, as well as another 525,000 m^2 of other special bridge surface.

If all surfaces on the bridges were used, even more square meters would be available for PV modules. But in the city center, where the bridge passes through built-up areas and must therefore be beautiful from all sides, little photovoltaics will be installed on and around the bridges.

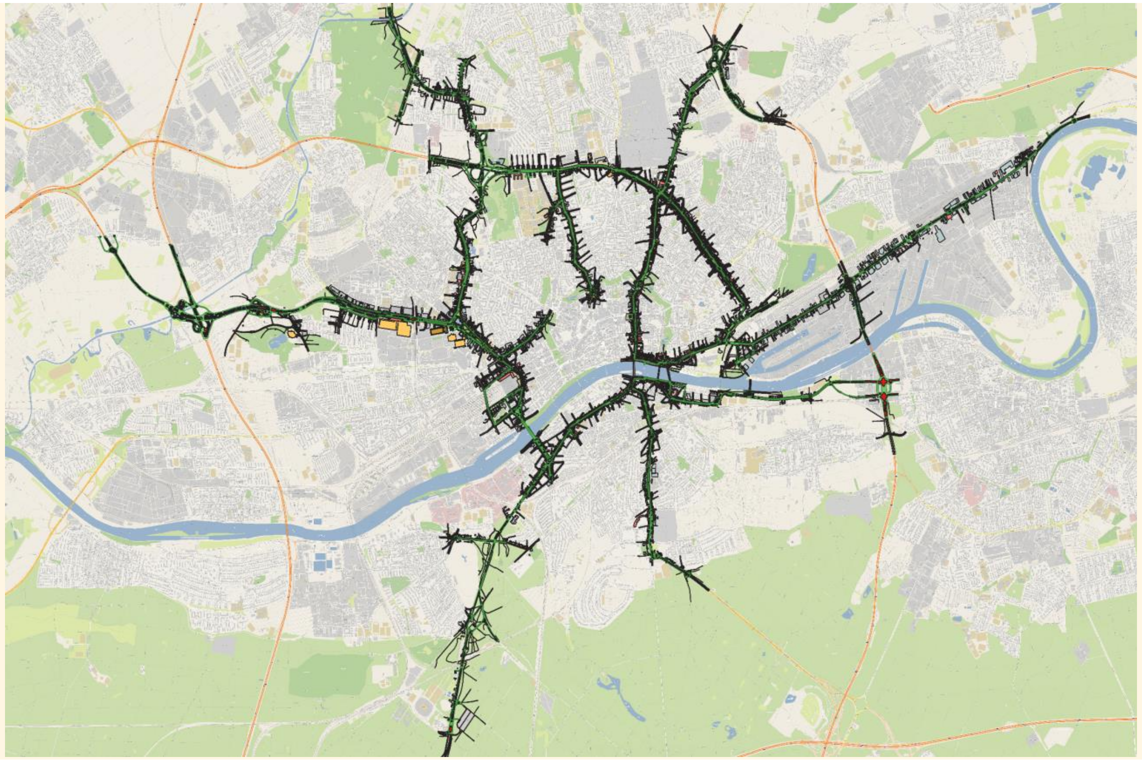
Even on the outer arms, where the bridges still pass through residential areas, photovoltaics are installed only aesthetically integrated.

Because it would be a pity if modern art or handicrafts on the sides of the bridges or on the columns would be aesthetically impaired or even covered by technical modules. In addition, many columns are overgrown with climbing plants that would cover the photovoltaics.

But as soon as the bridges lead out of the city and no residents are looking at them from the side (and no tall buildings on the right and left are shading them), all possible surfaces will be equipped with photovoltaics.

Therefore, the equipment of areas with photovoltaics may not be carried out everywhere in the same form, but must be segmented depending on the bridge section.

The entire bridge network was segmented according to the "degree of beauty" of the installable photovoltaics or the degree of inconspicuousness



Photovoltaics on the ring road and along residential buildings are planned to be aesthetically pleasing or extremely inconspicuous, while highly efficient classic solar modules can be installed on the outer arms in some sections

The energy calculations take into account (1) the tilt angle, (2) the direction, as well as (3) the aesthetic effect on the energy yield of the panels, and last but not least (4) the shading effect of the neighboring buildings and trees.

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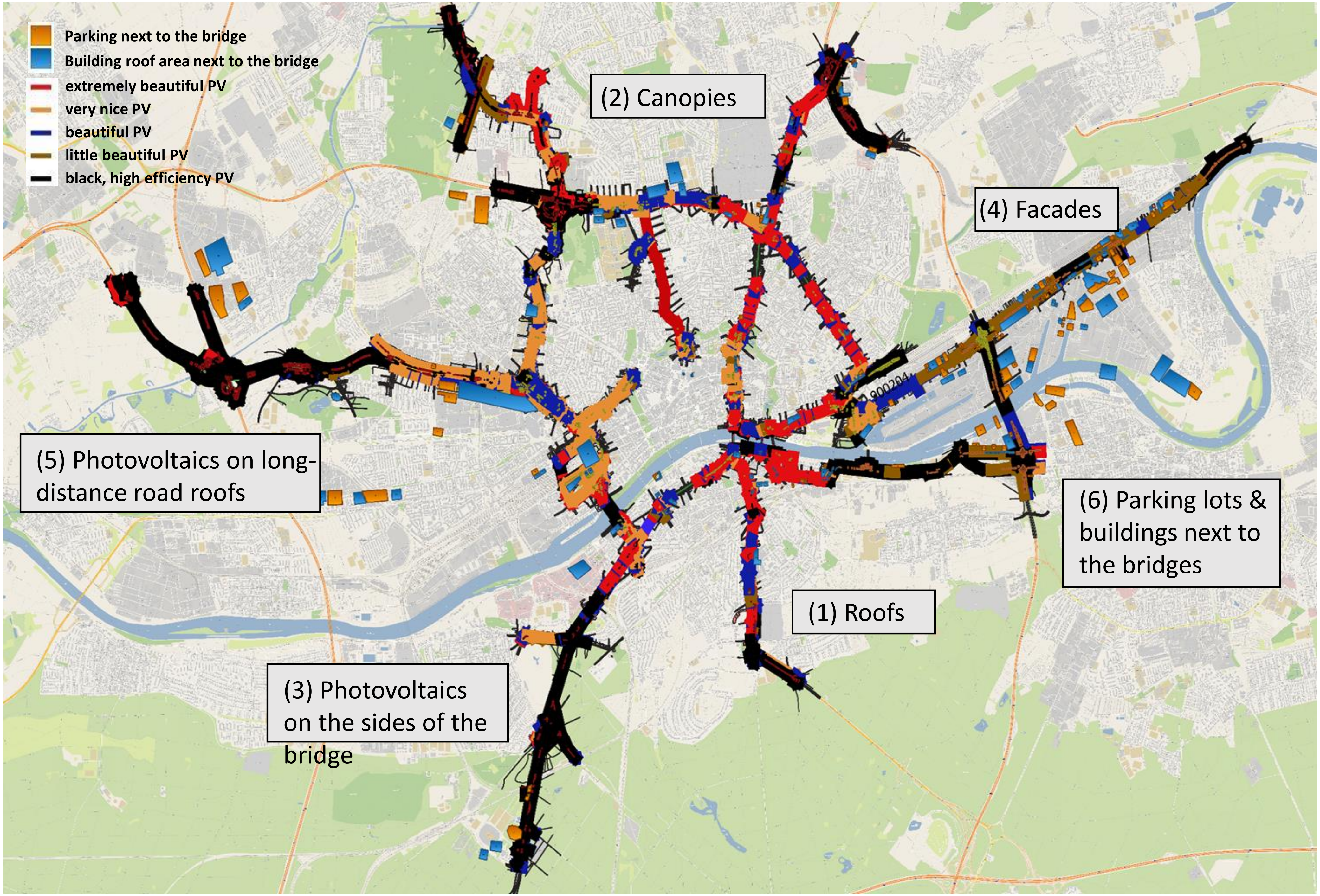
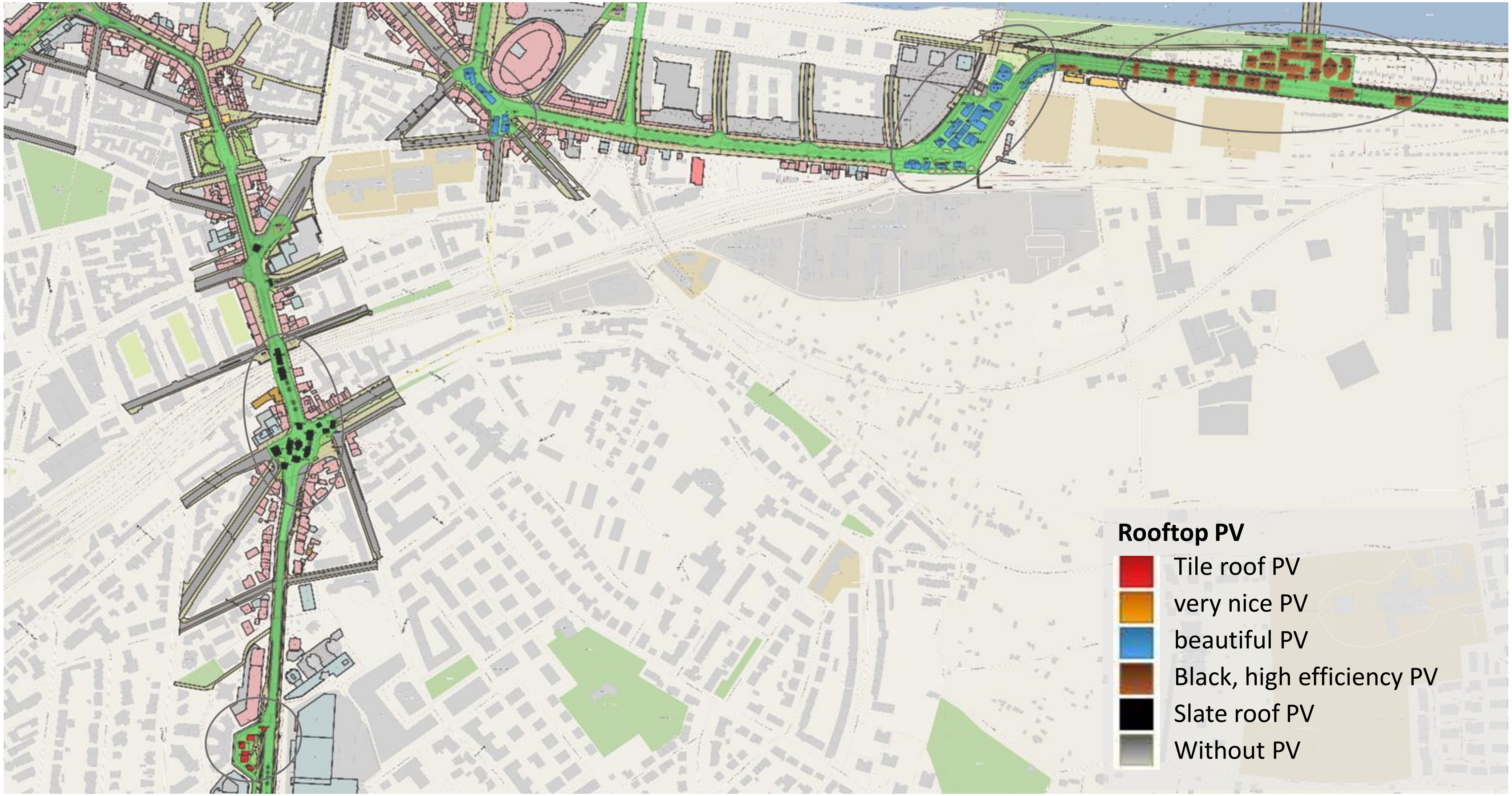


(1) The construction of the bridges will create over 500,000 m² of roof space on the bridge buildings, all of which could theoretically be used for photovoltaics - but even some of it can already generate 58 GWh/a of electricity



(1) Roofs: Green roofs on the bridges, roofs with large roof terraces or even roofs with special artistic features will not be able to be covered with photovoltaics

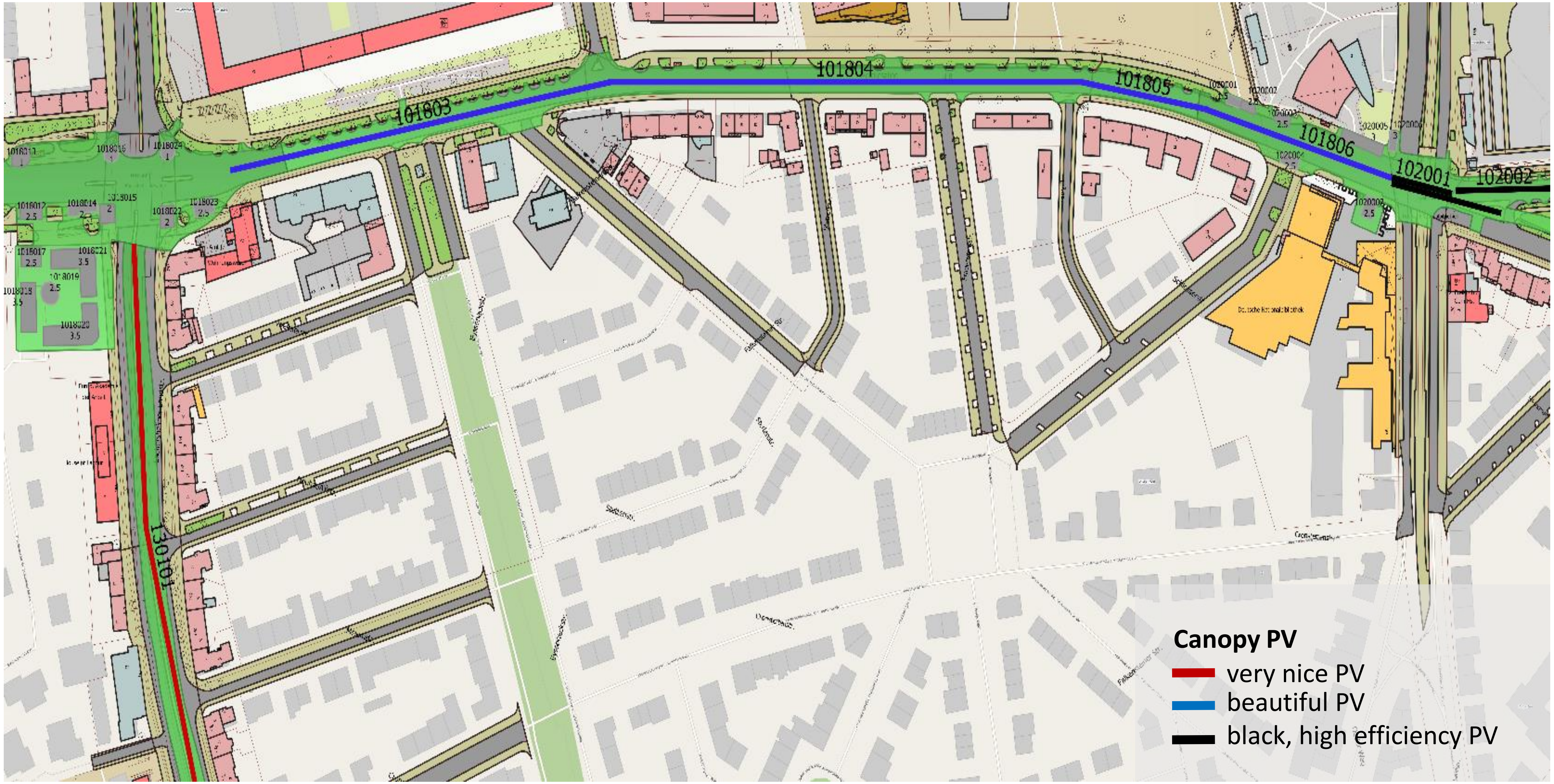
In the urban area of Frankfurt, one can "harvest" up to 275 kWh per square meter of photovoltaic surface per year with the most modern technologies, but only if it is an unshaded area on the roof with the appropriate orientation towards the sun.

Overall, however, PV modules with a slate or tile appearance are only installed on 80% of the roofs, which are mainly on the outer arms. Although these modules can be integrated aesthetically to a large extent, they have an efficiency ratio of only 12% (in contrast to high-efficiency conventional modules, where it is over 25.5%).

No PV at all is used on the roofs of downtown buildings, because industrially manufactured photovoltaic components - no matter how beautifully colored or shaped - do not go well with artisan-covered slate, copper, or tile roofs in downtown areas.

Since there are numerous other surfaces on Frankfurt's bridges where PV modules can be installed, it is possible to "afford" not to install photovoltaics on the roofs of the buildings on the inner city ring of bridges. The roofs there are built by the Master Academy of Arts and Crafts in the traditional style and have a cultural-historical function - so they make a valuable contribution to society in a different way.

(2) Canopies: The paths on Frankfurt's bridges are partially covered by canopies that protect pedestrians from the heat of the sun or rain and generate nearly 20 GWh/a of electricity.

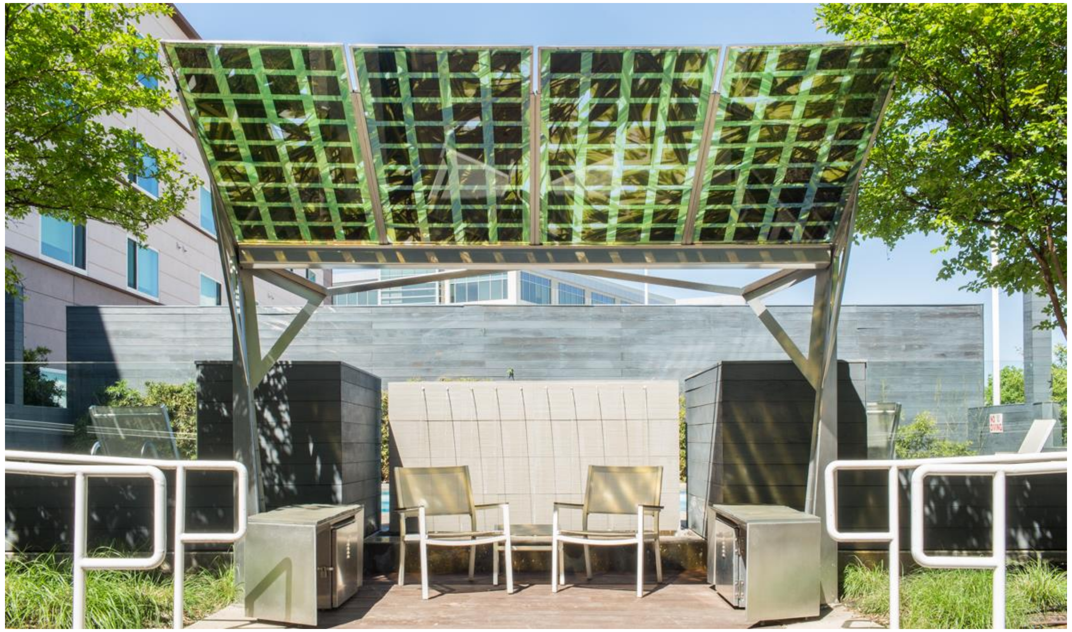


(2) The inner city canopies will be equipped with very beautiful PV modules, while the canopies on the outer arms will be covered with black high-efficiency PV modules.

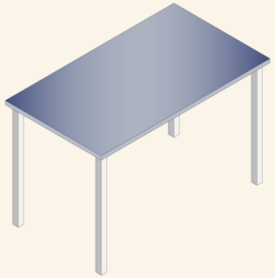
On the Frankfurt bridges, 100,000 m^2 of canopies for stations or path sections ("canopies") are being built.

Almost without exception, they can be covered with PV modules. In addition to flat roofs or roofs with slopes, there are also canopies with curved roof.

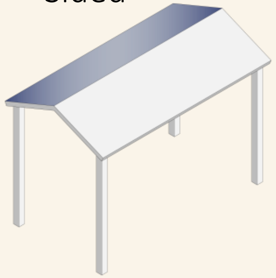
Five canopy types are envisioned for the Frankfurt bridges.



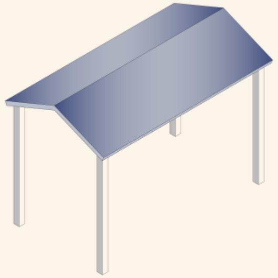
Flat & Horizontal



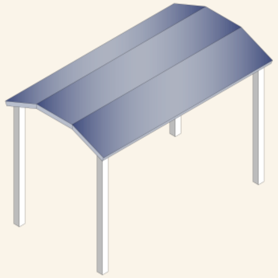
Oblique & Single Sided



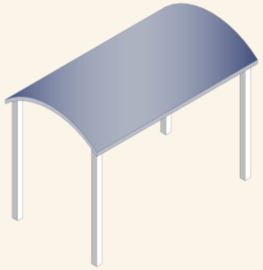
Oblique & Two-sided



Trapezoidal



Round



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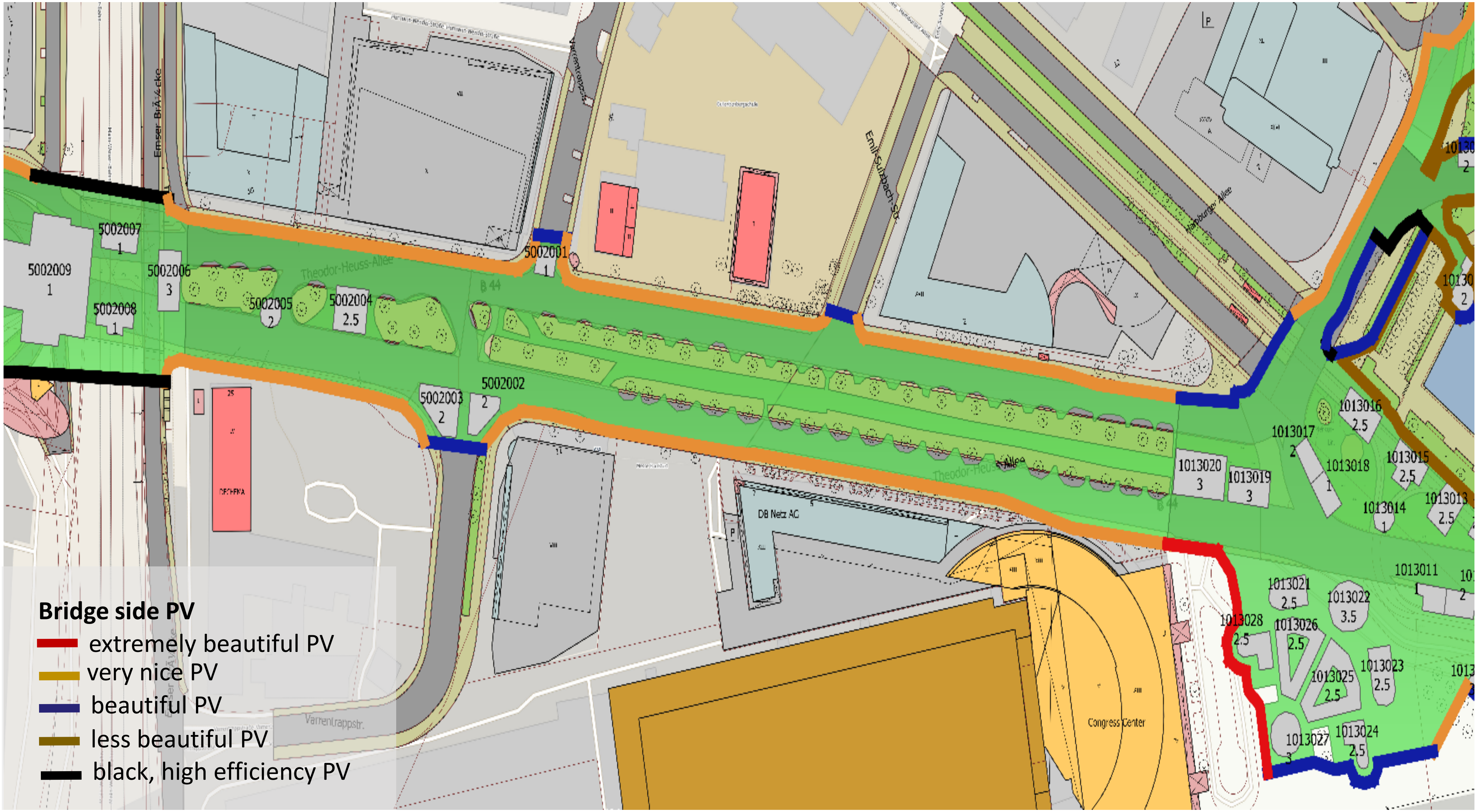
(3) Bridge sides: Photovoltaic modules will be installed vertically on the sides of Frankfurt's bridges - a total of 270,000 m^2 , generating approximately 31 GWh/a of electricity.



(3) The surface of the bridge sides will be equipped with 1.3 m or 2 m wide PV modules

Parameter	Value
Constants & Factors	
Inclination angle (°)	90
Effect Ratio (%)	25,50
Shadow factor= 1 (no shadows)	1,00
Shadow factor= 2 (partial shadows due to trees)	0,73
Shadow factor= 3 (partial shadows due to buildings)	0,60
Shadow factor= 4 (partial shadows from trees & buildings)	0,67
Shadow factor= 5 (full shadow due to buildings)	0,19
Aesthetics factor= 1 (extremely beautiful PV)	0,70
Aesthetics factor= 2 (very nice PV)	0,80
Aesthetics factor= 3 (beautiful PV)	0,85
Aesthetics factor= 4 (not very nice PV)	0,90
Aesthetics factor= 5 (black, high efficiency PV)	1,00
derived values	
Total length (m)	131.014
total surface (m2)	272.797
Total GWh (85% of the generated E)	**30,9**

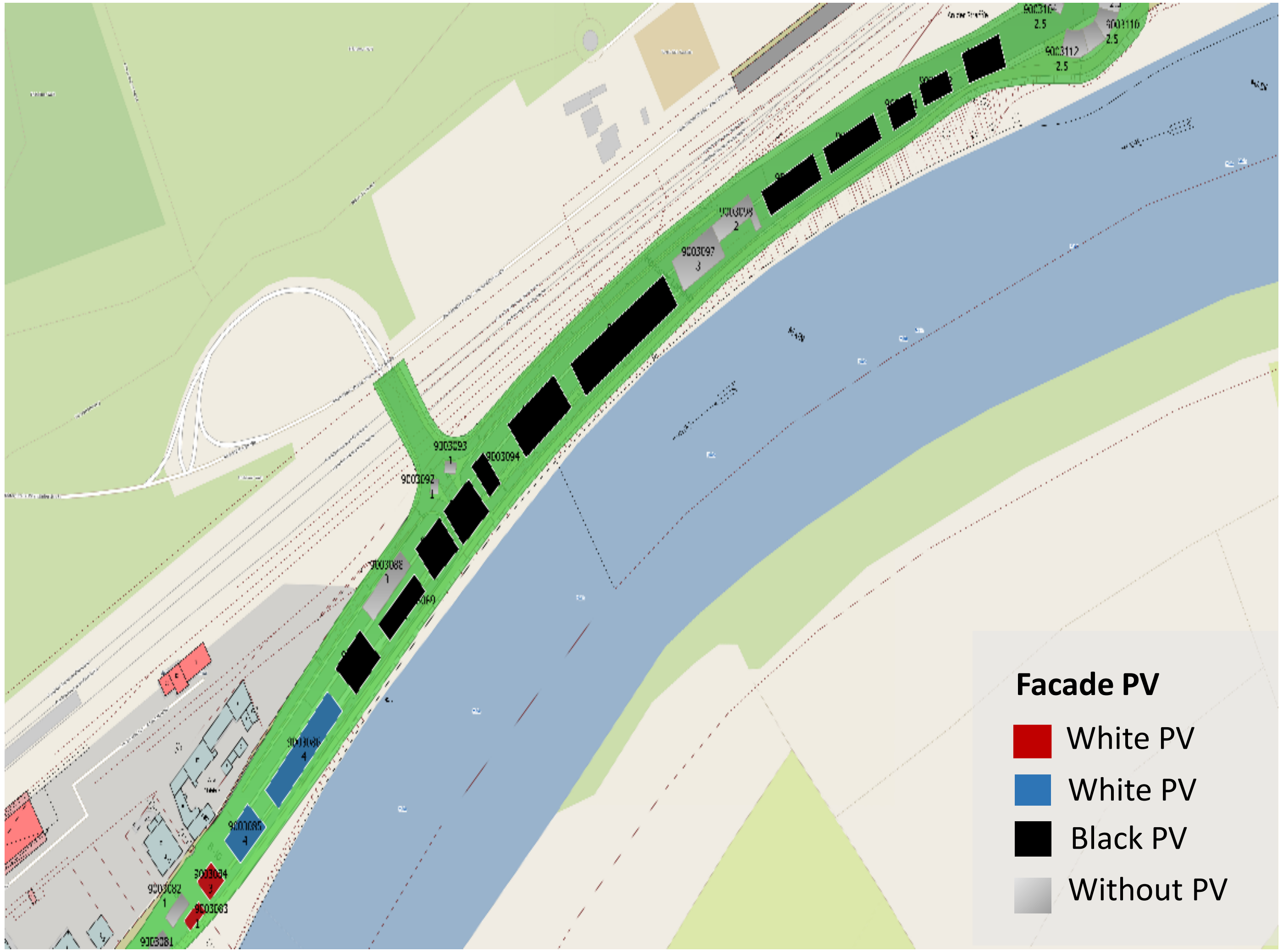
Sample excerpt from the calculation of the bridge sides

id	Postal	Direction(°)	Aesthetics	Shadow	Width (m)	Surface Area (m2)	E (kWh)
1001001	1001	85	2	3	2	71,2	6635,7
1001002	1001	85	2	3	2	17,6	1640,3
1001003	1001	60	2	4	2	47,4	5407,1
1001004	1001	65	2	2	2	46	5667,4
1001005	1001	10	2	3	2	12	1343,5
1001006	1001	125	1	2	2	54	4149,9
1001007	1001	-30	2	5	2	55,6	1938,1
1001008	1001	15	2	5	2	67,4	2382,7
1001009	1001	130	2	5	2	8,8	193,8
1001010	1001	140	2	5	2	106,4	2181,8
1001011	1001	80	2	3	2	14	1335,9
1001012	1001	40	3	3	2	34,4	3952,4
1001013	1001	35	3	5	2	113,6	4169,8
1001014	1001	35	2	5	2	95,8	3309,6
1001015	1001	85	2	4	2	17,4	1797,3
1001016	1001	65	3	1	2	32	5738,3

usw.

The aesthetics of the PV modules, as everywhere on the bridges, depends on whether or not the PV modules can be seen from buildings along the bridges. In certain places where the bridges are very high (e.g. at the IT college), the sides are equipped with PV modules up to a height of 4.5 meters.

(4) Facades: On Frankfurt bridges, only 12% of the building facades (approx. 70,000 m^2) are covered with PV modules - with them, a total of 5 GWh/a of electricity is generated.



White façade photovoltaics are used in buildings with residential development in the neighborhood, while black ones tend to be used where there are no residents to the right and left of the bridges.

Buildings that receive white PV façade modules are fitted with them on three sides; if black PV façade modules are used, only one side of the building is fitted with them.

(4) Most of the façade PV modules are located on the eastern outer arms, as they are easier to integrate into the façades of the modern architecture prevalent there.

(4) PV modules can also be cleverly integrated into the bridge buildings close to the city center - the potential would be added to the 5 GWh/a of bridge electricity generation.

(5) To supplement the power supply, highway canopies may be continued at the ends of the bridges

To minimize the expense of these PV installations, the "highway extensions" will only be installed where the highway runs straight, otherwise the expense of custom fabrication of the curved PV roof modules would be added. All seven arms of the Framkfurt bridges terminate over federal highways: A total of 30,000 m^2 of trunk road can be covered with such "extensions" and equipped with PV modules in the direction of the sun and at the optimal angle. This will generate a total of 7 GWh/a of electricity.

(6) Parking spaces next to bridges: Along the Frankfurt bridges, 380,000 m^2 of parking spaces can also be equipped with PV modules.

380,000 m^2 of photovoltaically activatable parking lot canopies are to be built on the right and left over the parking lots of DIY stores, commercial units or offices in the course of bridge construction - at no cost to the property owners. These have the advantage that their customers can get out and in of their vehicles protected in all weathers: dry feet in the rain and not in an overheated car in the summer. In addition, their employees or customers can charge the increasing number of e-vehicles during parking time via charging options at the stand columns.

Parkplätze entlang der Brücken

(6) Roofs next to the bridges: PV modules can be gently placed on 725,000 m² of roof space of companies and institutions along Frankfurt's bridges

Along the Frankfurt bridges are flat roofs of large corporate buildings or institutions, many of which are suitable for PV modules. For most property owners, rail systems and modules resting on load-distributing building protection mats are the most attractive, as they do not damage the thermal insulation and roof cladding.

By cooperating with the bridge company, property owners have a competent partner in the installation, operation, usage distribution and storage for the PV systems on their roofs - making the installation of PV modules on the roof convenient and advantageous for them.

(6) If all large parking lots and roofs along the bridges are equipped with black, high-efficiency PV modules at the optimal angle facing south, this can generate 277 GWh/a of electricity

Parking spaces of companies and institutions next to the bridge (exemplary extract)

id	Surface (m2)	Name	District	Shadow	Aesthetics	total solar surface (m2)	E (kWh/a)
1	1134	Parking AVis car rental	Hanauer Ldstr	3	5	1482	396041
2	4413	Bauhaus	Hanauer Ldstr	3	5	5766	1541207
3	1712	LIDL	Hanauer Ldstr	1	5	2237	738152
4	1554	Mainova	Hanauer Ldstr	1	5	2030	670028
5	10568	Hornbach	Hanauer Ldstr	3	5	13807	3690793
5	5711	Hornbach	Hanauer Ldstr	1	5	7461	2462374
6	10800	Parking lot Adam Opel Strass	Hanauer Ldstr	1	5	14110	4656565
7	4160	Parking place Möbelum I	Hanauer Ldstr	1	5	5435	1793640
8	1864	Parking lot Möbelum II	Hanauer Ldstr	3	5	2435	650988
9	8735	Parking lot Ex-Neckermann 1	Hanauer Ldstr	1	5	11412	3766213
10	11331	Parking lot Ex-Neckermann	Hanauer Ldstr	1	5	14804	4885513
11	3464	Parking lot BLG Handelslogis	Hanauer Ldstr	1	5	4526	1493550
12	8369	Lost and found	Hanauer Ldstr	3	5	10934	2922809
13	4129	Parking lot Find Fachgroßhan	Hanauer Ldstr	1	5	5394	1780274
14	3767	Crytec PP I	Hanauer Ldstr	1	5	4922	1624193
15	3727	Parking lot unbennant building	Hanauer Ldstr	3	5	4869	1301626
16	8587	Parking lot R&M Cars	Hanauer Ldstr	1	5	11219	3702400
17	20837	Siemens PP	Hanauer Ldstr	1	5	27223	8984152
18	2997	Parking lot 385 ideal Studio	Hanauer Ldstr	1	5	3916	1292197
19	547	Parking lot Hertz Car Rental	Hanauer Ldstr	3	5	715	191036
20	1139	Parking lot Still branch	Hanauer Ldstr	1	5	1488	491095
21	1952	Parking lot Roth Energy	Hanauer Ldstr	1	5	2550	841631

In total, 417 GWh of electricity per year can be generated with PV modules on and along the bridges

The largest contribution to this on the bridges is made by the roofs of the bridge buildings with 58 GWh/a, as they can be aligned at an optimal angle of 37 degrees to the sun on flat roofs that cannot be seen. In second place are PV modules mounted on the sides of the bridges with 31 GWh/a. These are vertically integrated, i.e. are only "splayed" from the bridge side to a limited extent or in some places at the optimal angle towards the sun.

However, large parking lots and buildings next to the bridges offer the greatest potential: Since most of them are located along the outer arms of the Frankfurt bridges and can hardly be looked down on from residential buildings, large parts of their surface are covered with highly efficient PV modules that are optimally oriented towards the sun and produce a total of 277 GWh/a, almost twice as much as the PV modules directly on and next to the bridges.

Power generation

Photovoltaics	total area (m2)	total E (GWh/a)	Shares E (%)	Shares on & next to the bridge (%)
Bridge side	272.797	31	6,07	
Canopy	97.040	20	3,86	
Roof area	476.026	58	11,44	
Facade	70.763	5	0,92	
Windows	17.691	0,5	0,09	
Column	22.318	0,1	0,02	27,11
Elevator	1.200	0,3	0,05	
Stations	5.000	1	0,20	
Extension Bridge & Highway Canopy	108.054	24,6	4,77	
SUM	**1.070.888**	**140**		
Parking spaces	498.420	135	26,52	
Building next to the bridge	723.350	142	27,71	72,89
SUM	**1.221.770**	**277**		
TOTAL	**2.682.278**	**417**	**100**	**100**

An extension beyond bridges: energy bands on the highways

Electricity production by PV modules does not have to end at the outer arms of bridges - it can continue installed on pylons, along highways and interstate roads

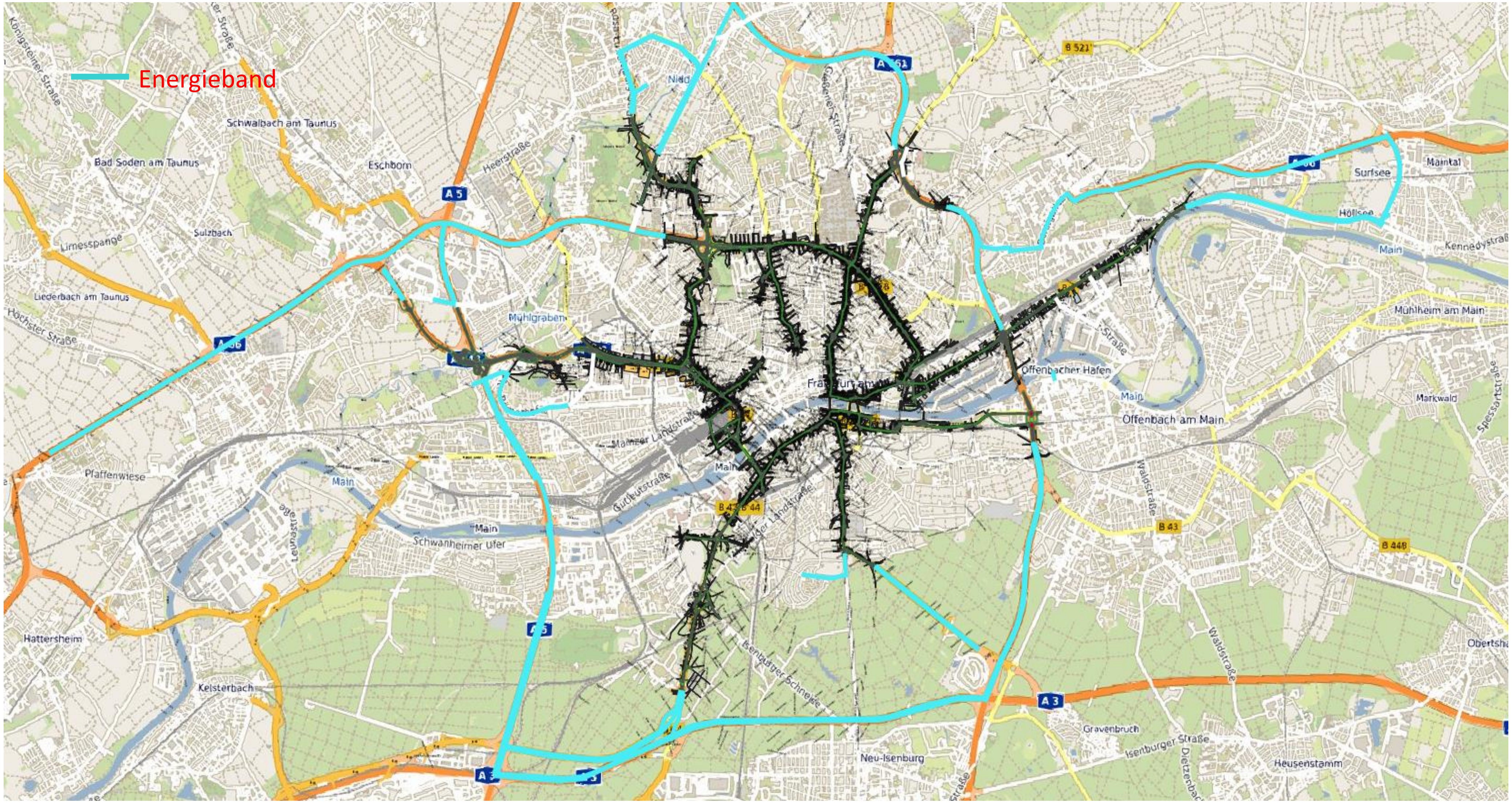
The concept of energy bands is easy to implement, comparatively inexpensive, and not invasive to nature or humans

Approximately every 15 meters, a pole made of iron trusses is erected, similar to conventional electricity poles, only much smaller: the truss construction saves material and ensures that motorists maintain a clear view along the road.

At a height of about 5 m, the masts are connected to each other and photovoltaic modules are mounted on the connecting webs in a row (like a ribbon) between the masts. A second row is placed about 2 m above the first, so that the shading of the lower row remains slight.

The PV modules have a width of 1.50 m and are aligned at the optimum angle to the sun. They are highly efficient black PV modules. Since they are installed over the edge of roads that are already dark gray, they can be installed for kilometers without causing a negative albedo effect or heating up the small-scale climate around them.

Around 100 GWh/a can be generated with the help of approx. 60 km long energy belts around Frankfurt

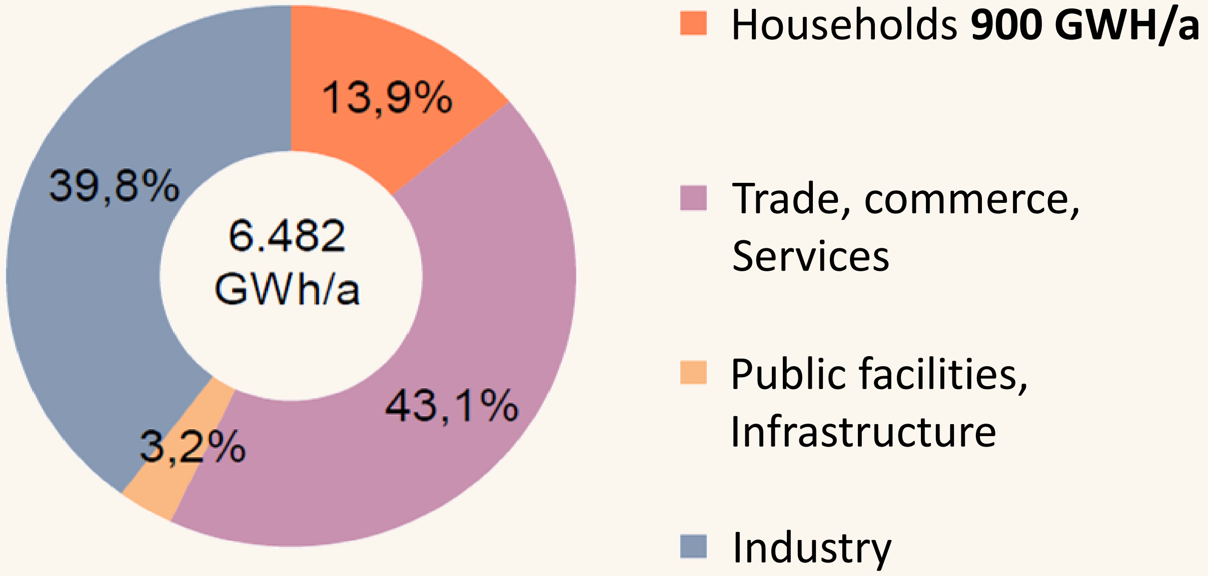


This potential could be increased by a further 20% by energy bands running across the highway at heights of 5 and 7 m respectively

140 GWh/a from bridge PV modules, 277 GWh/a from PV along the bridges, and 100 GWh/a from energy bands - the 517 GWh/a is equivalent to more than half the amount of energy for Frankfurt households' electricity needs

Electricity consumption by sector

Energy Profile Frankfurt 2018



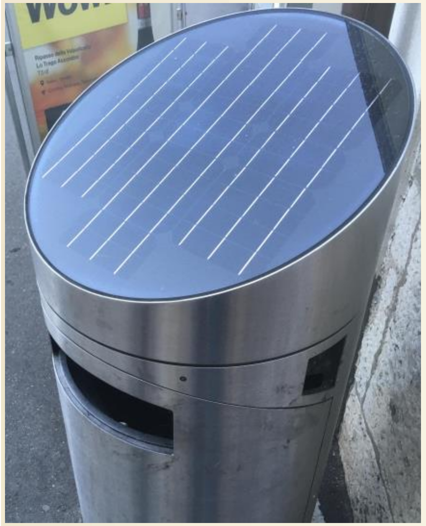
However, the actual optimal use of these enormous amounts of additional electricity must be determined by the local supplier, Mainova: 140 GWh/a of this is consumed by the Frankfurt Bridges neighborhood itself. A large part of the remaining 377 GWh/a flows into green hydrogen production and vehicle supply along the bridges.

Old New Territory
Frankfurt

Photovoltaics always and everywhere.

Even if it looks nice or isn't visible at all - is that much electricity right around people even healthy?

Old New Territory
Frankfurt



Photovoltaics always and everywhere: How harmful is it?

Nowadays, people are exposed to various electric, magnetic and electromagnetic fields on a daily basis. A DC magnetic field is generated in conductors through which DC current flows, while a changing AC electromagnetic field is generated in a conductor through which AC current flows.

Not everyone is comfortable with the idea of being surrounded on all sides by electricity production. And some of these fields are indeed suspected of having harmful effects on our bioorganism under certain circumstances.

On the bridges in Frankfurt, attention is therefore paid everywhere to electromagnetic environmental compatibility and compliance with strict limit values. Electrosensitive people in particular react strongly to the fields, which is why installations on the bridges are made after testing and in-depth analysis of potential electromagnetic fields.

No increased health hazards are to be expected from a photovoltaic system if it is installed professionally

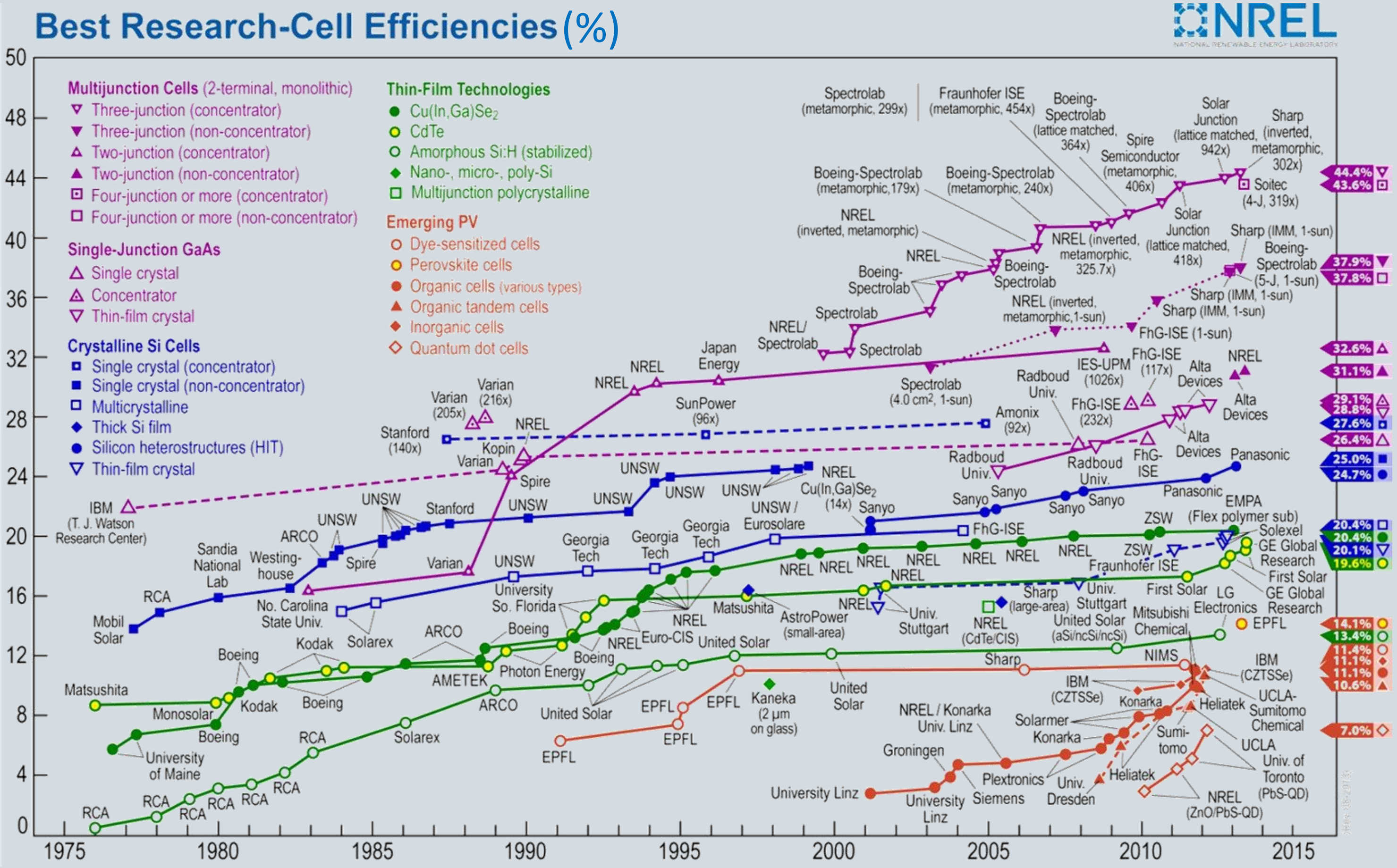
The zoologist and researcher on the magnetic sense of animals, Professor Dr. Hynek Burda (Duisburg), investigated in a study the influence of low-frequency fields on melatonin secretion in the body and came to the conclusion that calves exposed to alternating electromagnetic fields produce less of the sleep hormone melatonin in winter than in summer - with the effect reversing in summer.

The causes of this are unclear and not yet researched, but from some effect of magnetic fields on the human organism can not be excluded.

Therefore, it is crucial to professionally reduce the effects of magnetic fields to a completely harmless level when planning integrated photovoltaics: Laying DC lines of the PV system as close as possible to each other to reduce alternating magnetic fields, paying attention to low line loop formation, maintaining distances to the inverter - if available, professional grounding, etc. are among the rules that specialist companies all apply.

The additional electrosmog pollution caused by a PV system is also correspondingly low from a building biology point of view and harmless to health if executed correctly.

Sustainability starts with the selection of PV technology: Above all, the PV modules should be free of pollutants or at least low in pollutants during production and disposal.



Unfortunately, the most efficient technologies are not always the most environmentally friendly:

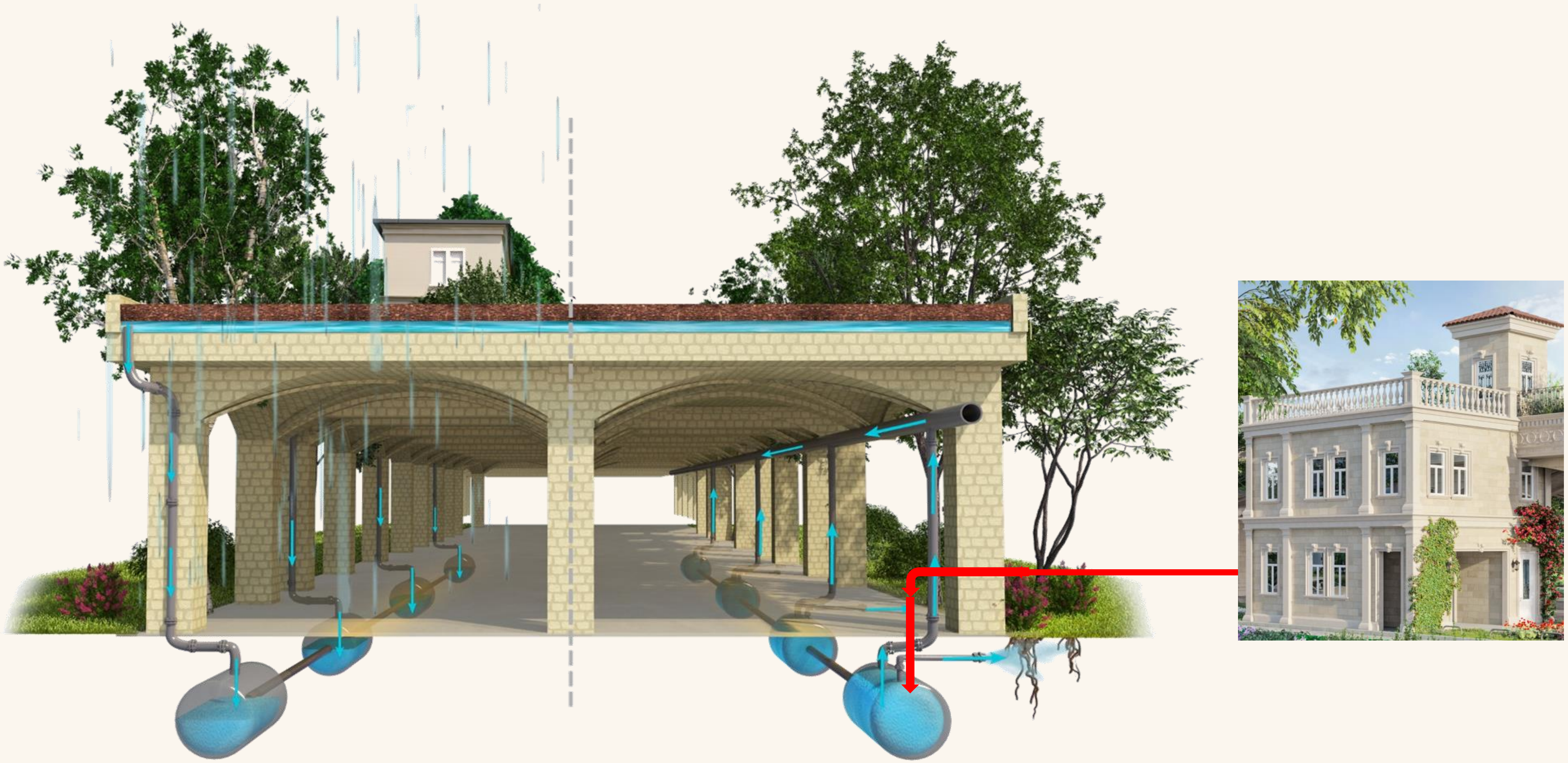
Some solar technologies contain toxic chemicals such as cadmium telluride, copper indium selenide, cadmium gallium (di)selenide, copper indium gallium (di)selenide, hexafluoroethane, lead and polyvinyl fluoride. These chemicals are not on the bridge solar modules.

With the expansion of wind and solar power, there will be an increasing abundance of energy at peak times

On an annual average, wind and photovoltaic systems are so effective that Germany will not only have enough electricity, but in the future, after the generous expansion of these technologies, even more than enough. The problem: Depending on the wind and sun, the electricity is not necessarily produced at the time it is also consumed. Whenever more electricity is produced than is consumed, plants that produce green electricity must either be shut down, or the electricity must be sold abroad or to surrounding areas, or sold at negative prices. Especially because electricity storage options such as batteries and pumped storage power plants are currently only available to a very limited extent, there is then too much electricity at certain times that cannot be usefully used anywhere without storage. Because of this "surplus" of electricity, the number of hours when electricity is sold at negative prices has increased significantly in recent years: Anyone who wants to sell electricity still has to pay the buyers money in this case. This is because there must not be too much electricity in the grid, as the power grid should not be overloaded, otherwise there is a risk of outages.

Photovoltaic energy at peak times in abundance
Where can you store them?

For extreme energy surpluses, in summer there is also the possibility of temporarily heating the water in the cisterns under the road a few degrees to "get rid" of energy there, so that the networks are not overloaded



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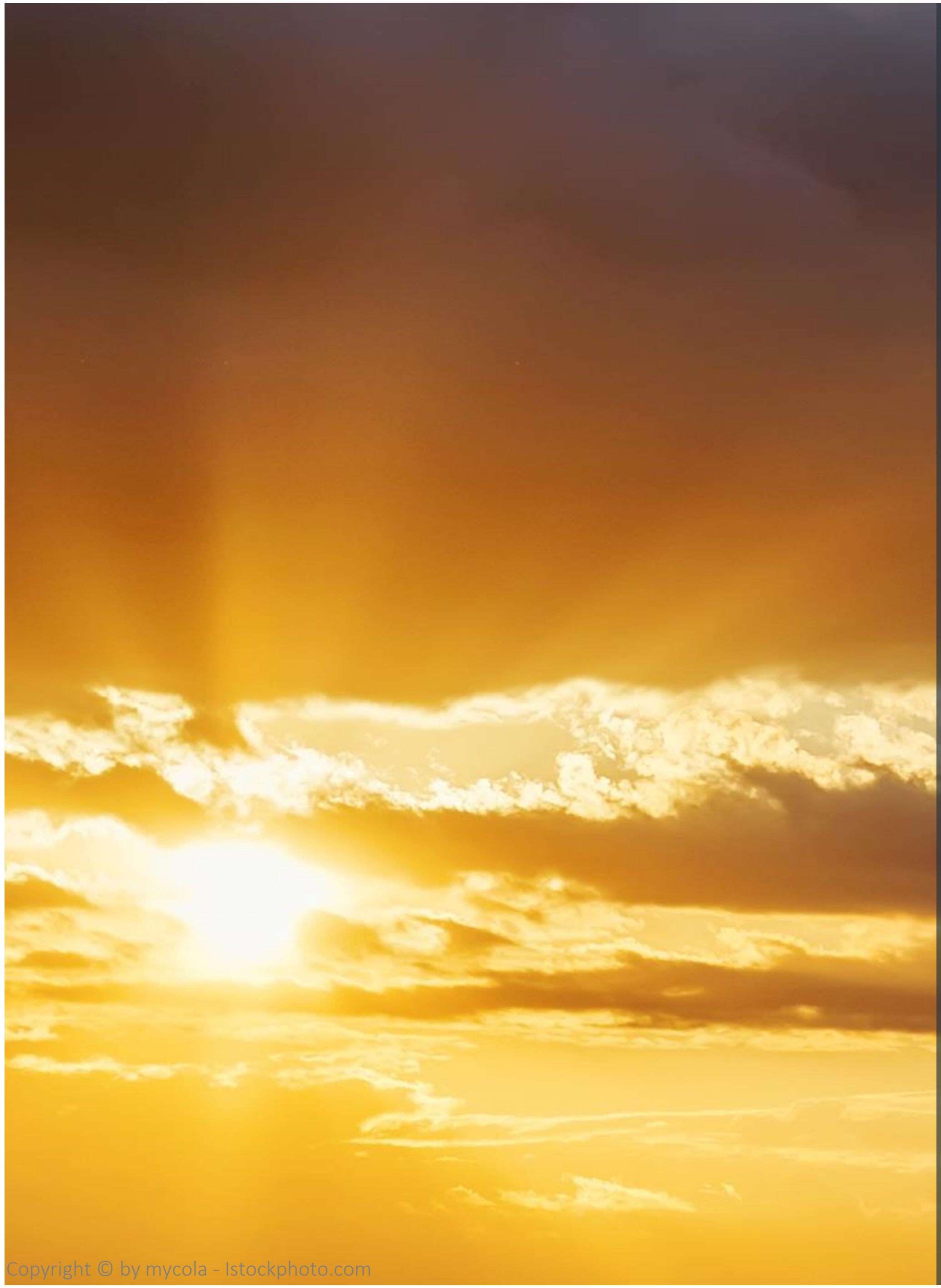


Conclusion: the bridges not only produce a surplus from neighborhood electricity generation, but as an infrastructure network they also enable electricity generation in their immediate vicinity

With 1 million square meters of photovoltaic surface on the bridges, 140 GWh/a of electricity can be produced. A further 277 GWh/a can be generated by PV modules in the vicinity of the bridges. And another 100 GWh/a of electricity can be generated by extension in the form of energy ribbons at the ends of the bridges.

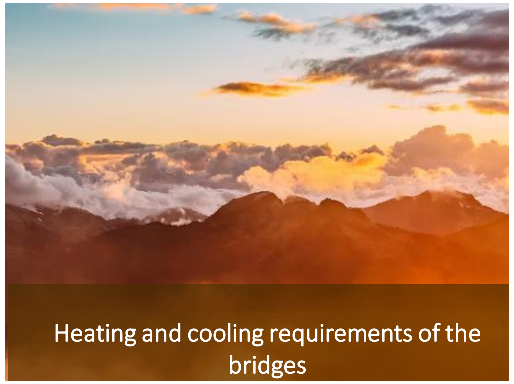
The bridges only require around 140 GWh/a for their own residents, businesses and infrastructure. This means that they could use the remaining 377 GWh/a to supply Frankfurt's population with renewable, green electricity.

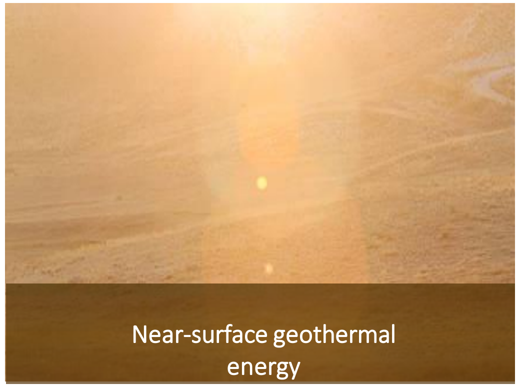
The massive equipment of residential quarters with photovoltaics must be carried out professionally so that they have no impact on the health of the residents. This must be an integral part of the planning process, as must the selection of pollutant-free PV modules.

Old New Territory Frankfurt


Electricity demand on the Frankfurt bridges


Photovoltaics as quarter power


Heating and cooling requirements of the bridges


Near-surface geothermal energy


The energy infrastructure of the future


The bridge world


Sustainability through technology


The Co2 balance of bridges

EMPLOYEES

Architecture	Geoinformation	Urban climate - world climate	Water	Law	**Critical sparring partners:**
Image & photo	Green & Nature	Statics	Packing	Finance	Professors
Bridges	Communication	Transportation	Webpage & Design	Implementation	Professionals
Energy	Art & Culture	Technology & IT			Inspirers & Supporters

Near Surface Geothermal Energy

Around 438 GWh/a of thermal energy is generated or collected by Frankfurt bridges and forwarded for storage

With the help of the 15,000 columns of the Frankfurt bridges, around 35 GWh of thermal energy can be extracted from the ground each year - a classic use of near-surface geothermal energy.

In addition, 1 million square meters of PVT solar modules on and along the bridges can generate around 303 GWh of thermal energy per year. Another 100 GWh/a can be generated by waste heat from data centers and industrial parks in Frankfurt. Of this total of about 403 GWh/a of thermal "energy harvest," 107 GWh/a can be consumed in winter immediately after generation. The remaining 296 GWh/a can be stored in the ground with the help of several thousand borehole thermal energy storages (BTES), so that at an efficiency factor of about 30% to 35%, about 92 GWh/a can be extracted and used again for space heating in winter.

Old New Territory Frankfurt

Chapter content: Natural geothermal heat is extracted from the ground and, in addition, heat collected above ground is stored in the ground

The soil in Frankfurt is comparatively warm near the surface, with a temperature of 14 °C. The columns of the Frankfurt bridges project with their foundation piers 15 to 20 m deep into the ground. Probes in the pillars can realize space heating or cooling for the buildings on the bridges through thermal exchange as required.

The heat that accumulates behind the photovoltaic surfaces - with an environmentally compatible liquid as a carrier - is sent down into the depths through probe fields, stored there and brought back up again as needed. The probe fields can be installed in the course of the bridge construction in the (anyway) torn up ground and project down to a depth of 250 m.

Both systems use de facto solar energy and not geothermal energy from the glowing center of the earth, as ground-source or "classical" geothermal energy does.

Old New Territory
Frankfurt

Geothermal piles can be used to extract heat available in the ground for heating, or to send solar heat collected above ground down into the ground and store it there until it is extracted

Geothermal piles under Frankfurt's high-rise buildings have both functions

Classic geothermal energy via foundation piles in the ground is already being used in Frankfurt, especially for high-rise buildings: Here, for more than 20 years, it has been considered directly during construction to have the foundation piles go 30 to 100 m deep under a high-rise building and to equip them with line loops (probes) in order to use the so-called "near-surface geothermal energy", but also to transport heat that accumulates - especially through the large window fronts - down into the ground in order to regenerate it or to store the heat there in summer for extraction in winter.

Unfortunately, however, this cannot be transferred to other buildings with a citywide roll-out, as the subsequent installation of deep, geothermally utilized foundation piles in existing buildings is impossible.

Two basic mechanisms for heat transport are used on the Frankfurt bridges:
I) The foundation pillars of the bridge columns are equipped for convective heat transport.
&
II) in the immediate vicinity of the bridges, probe fields for conductive heat transport will be created.

Convective heat transport

Here, the heat transport is dependent on the groundwater temperature and, above all, the groundwater flow: If the groundwater (and thus the ground in which the probes are located for the purpose of heat extraction) has a temperature of 14 °C, for example, but flows slowly or hardly at all, then the site will cool down over the years because not enough water with the temperature of 14 °C will flow in.

Correspondingly, the effectiveness of convective heat transport depends on the porosity of the soil and the resulting flow velocity of the groundwater: In more porous soil, the water flows faster.

In Frankfurt, large parts of the ground are suitable for convective heat transport: it is estimated that 12,750 of the bridges' 15,000 columns can be designed for this purpose.

Conductive heat transport

Conductive heat transport occurs along temperature gradients: Depending on the thermal conductivity and heat capacity of the subsurface, heat can be sent into the ground and stored there: The ground environment of the probes stores the heat until it is extracted again at a later time.

How well heat can be stored depends on the rock type and porosity, but also on the water saturation: A certain saturation in itself is not bad for heat absorption, but if the water has too high a flow velocity, too much heat is transported away instead of remaining stored locally.

During the construction of the Frankfurt bridges, probe fields will be installed mainly north of the Main River, where the Frankfurt clay with good storage properties occurs in greater quantities.

The hydraulic permeability of the soil has a decisive influence on heat transport. Frankfurt has relatively sandy soil in the south, while in the north there is often "Frankfurt clay" directly below the surface.

With high hydraulic permeability, the propagation of the so-called "heat plume" is clearly characterized by convective heat transport - which is positive if one is only dependent on ground heat (i.e. on the influx of heat through groundwater). For thermal storage in the subsurface, on the other hand, the high hydraulic permeability of heat collected oberidically is less suitable. Since groundwater can be found almost everywhere in Frankfurt on the first 20 meters in depth, 85% of the piles of the bridge columns can be equipped with probes for convective heat transport.

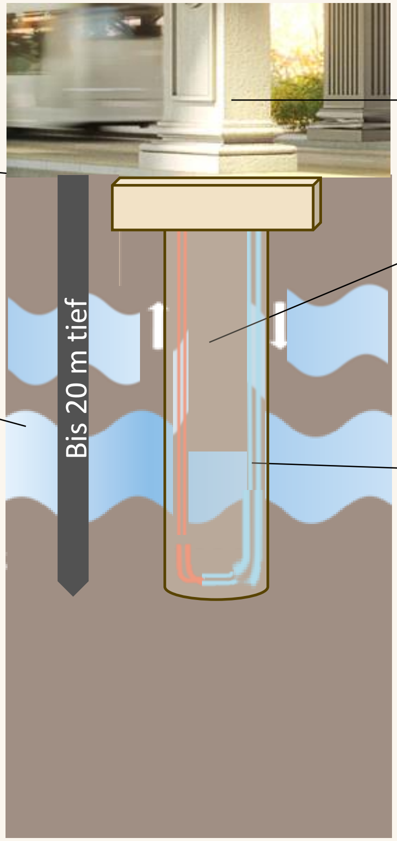
With low hydraulic permeability, the propagation of the heat plume is predominantly characterized by conductive heat transport: Although this is unsuitable for the extraction of the soil's own heat, since there is no "replenishment" of heat by groundwater. However, it is all the better for thermal storage of heat collected above ground in the subsurface.
In the course of the construction of the Frankfurt bridges, the road surface will be renewed in each case, so that probe fields can be installed in the roadside area along the bridges on this occasion.

Both geothermal concepts are used on the bridges: The columns extract heat from the ground there totaling 35 GWh per year for heating. Independently, about 403 GWh of heat is collected annually: Around 303 GWh is added by PVT modules and another 100 by waste heat from data centers. The portion of this generated in summer is stored in the ground, while the portion generated in winter is consumed directly.

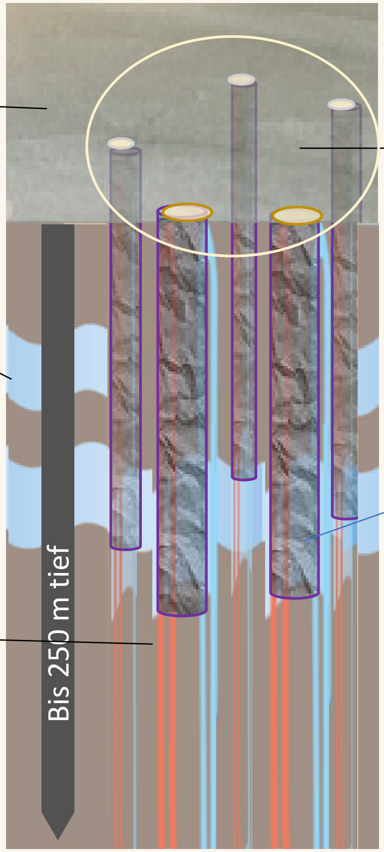
Depending on whether the heat already in the ground is used or the solar heat collected above ground is sent into the ground for storage, different borehole heat exchanger installations must be used.

Heat exchange between the soil and the probes takes place at the Frankfurt bridges using two systems

Geothermally activated pile: Probes in the pile transport ground heat upwards



Probe field: probes are used to store heat collected above ground



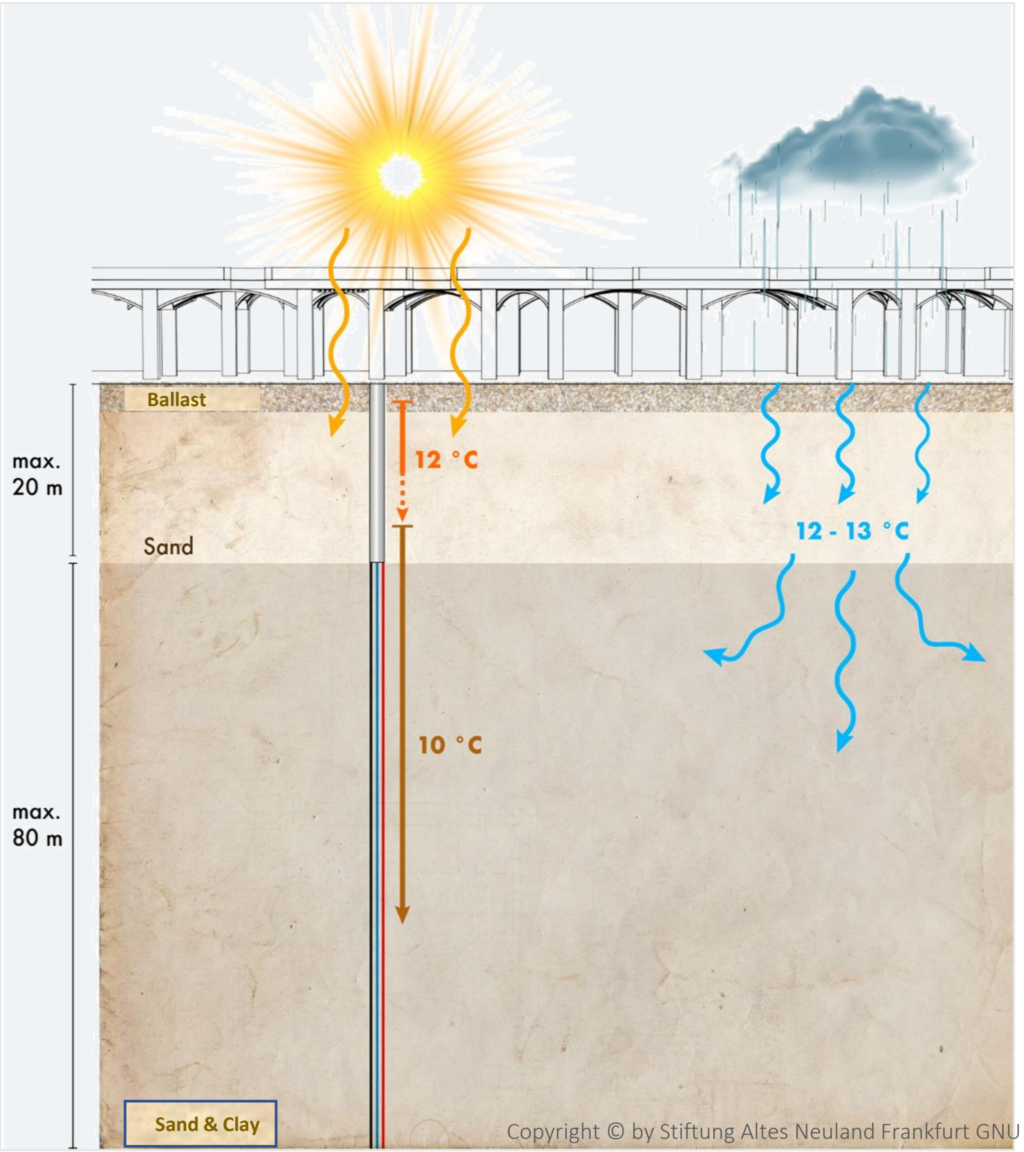
Case 1: The Frankfurt bridges use ground heat by extracting its heat from the ground via the piles of their columns, in which probes are mounted

The columns of the Frankfurt bridges reach down to a depth of twenty meters to extract a total of 35 GWh/a of energy: During the construction of the columns, before the reinforcing steel is lowered into the borehole to be filled with concrete, "probes" (black plastic tubes) are inserted into them on the inside. Later, the brine flows through them, transporting heat up from the ground in winter and vice versa down from above in summer.
The energy piles of the Frankfurt bridges have a diameter of 90 cm.

In the uppermost 10-15 meters, the soil temperature is determined by the climate, i.e. atmospheric factors such as solar radiation, air contact and the temperature and amount of rainwater that seeps away (below this, down to a depth of about 50 meters, the temperature is a constant 10 °C throughout the year, according to a rule of thumb for Central Europe). Due to its location in the Upper Rhine Graben, the soil temperature in Frankfurt is about 12 °C or more in many places from a depth of 2 meters.

Near-surface geothermal energy does not use the earth's core heat

The pillars of the Frankfurt bridges are founded about 20 meters deep and are equipped with geothermal probes. Even there, the geothermal heat of the earth's core is far from being reached as it is revealed by the beautiful geysers in Iceland, but only uses the solar heat that penetrates the earth's surface.



How much heat the soil of a region stores depends not only on the climate of the region, but also on the composition of the soil. Everyone is familiar with the effect: some materials heat up quickly in the sun, but also give off the heat again quickly when it gets cold; other materials, on the other hand, take a while to warm up, but then they also retain the heat.

The amount of energy that can be stored in or extracted from the ground near the surface depends on 1) the climate of the region and 2) the geological composition of the subsurface.

As part of the preliminary planning for the Frankfurt bridges, which will take several years, geological surveys must be carried out for each section of the bridge route to determine how it is built up and how warm it is or can become when energy is added. This is because some layers store heat better, others less well.

The soil beneath a city is usually very heterogeneous, and Frankfurt is no exception. In layman's terms and in a generalized way, one can say that south of the Main River it tends to be sandy, while north of the Main River one quickly encounters clay when digging. If a column pile is placed in a sandy environment, it absorbs heat more easily, but also releases it more quickly. Clayey soil, on the other hand, takes longer to heat up, but then also retains the heat longer.

So close to the earth's surface, another important factor for the heat storage capacity of the soil is the groundwater, which is encountered after only a few meters when digging in Frankfurt: If a lot of groundwater seeps through the soil at a relatively high rate (as is the case with very sandy soil), then this can have consequences for the heat supply of the piles upwards in two directions: On the one hand, it means that there is always a certain base temperature "flowing in," because the groundwater under Frankfurt has between 12 and 14 °C - in some cases even more. On the other hand, additional heat that is transported down into the earth by the piles in summer is also transported away again more quickly.

So if you want to calculate how much heat you can get from the ground of Frankfurt or how much you can store there, you need complex geothermal calculation models for different geological sections.

3) Groundwater is the third important factor for the heat storage capacity of a soil.

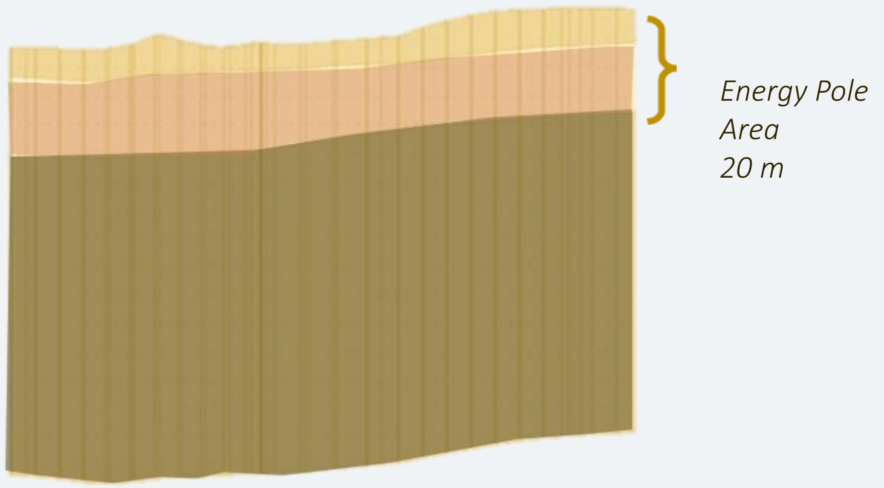
The groundwater under Frankfurt has an average temperature of 12 to 14 °C, similar to the soil through which it flows. The piles of the columns extract heat from the ground in winter, but also feed large amounts of heat back into it in summer (otherwise ground cools over the years).

Now, it is easy to imagine that groundwater flows faster in sandy soil than in clay layers. When it "washes around" the piles, they can absorb the ambient heat, which averages 13 °C, very well - better than from "dry" soil. But if the piles conduct heat down, then this is also partly taken along or washed away by the groundwater.

Therefore, it is important to determine the flow rate per soil layer in order to deduce how capable a soil is of storing water in the long term.

The flow velocity of groundwater near the surface is low in most places in Frankfurt. But there are also isolated rip currents. There is currently no comprehensive groundwater model for Frankfurt.

In Frankfurt, groundwater is encountered after a depth of about 2 to 5 meters, depending on where you dig. These are not yet rushing rivers (there are also, but usually much deeper), but moisture that seeps through the ground.

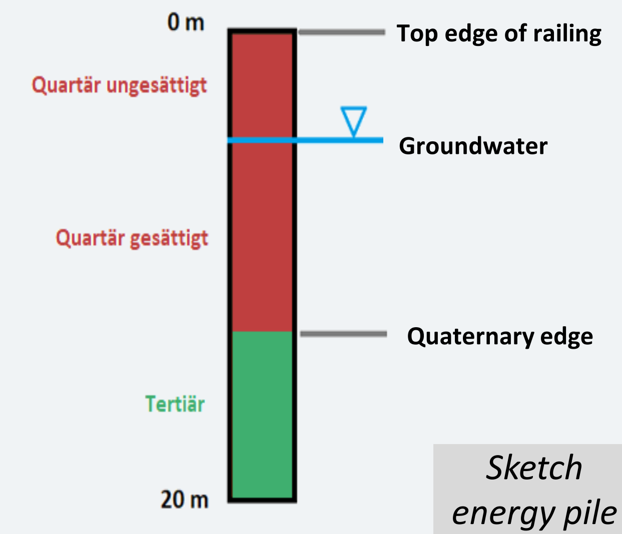


One energy pile of a column of the Frankfurt bridges can extract an estimated average of 1 kW of heat from the ground

This results from the consideration of how much heat extraction per meter (W/m) is possible: This differs from earth layer to earth layer, therefore it is weighted with the "thickness", the experts speak of "thickness", of the respective earth layer. - i.e. respective (W/m) x respective thickness (m).

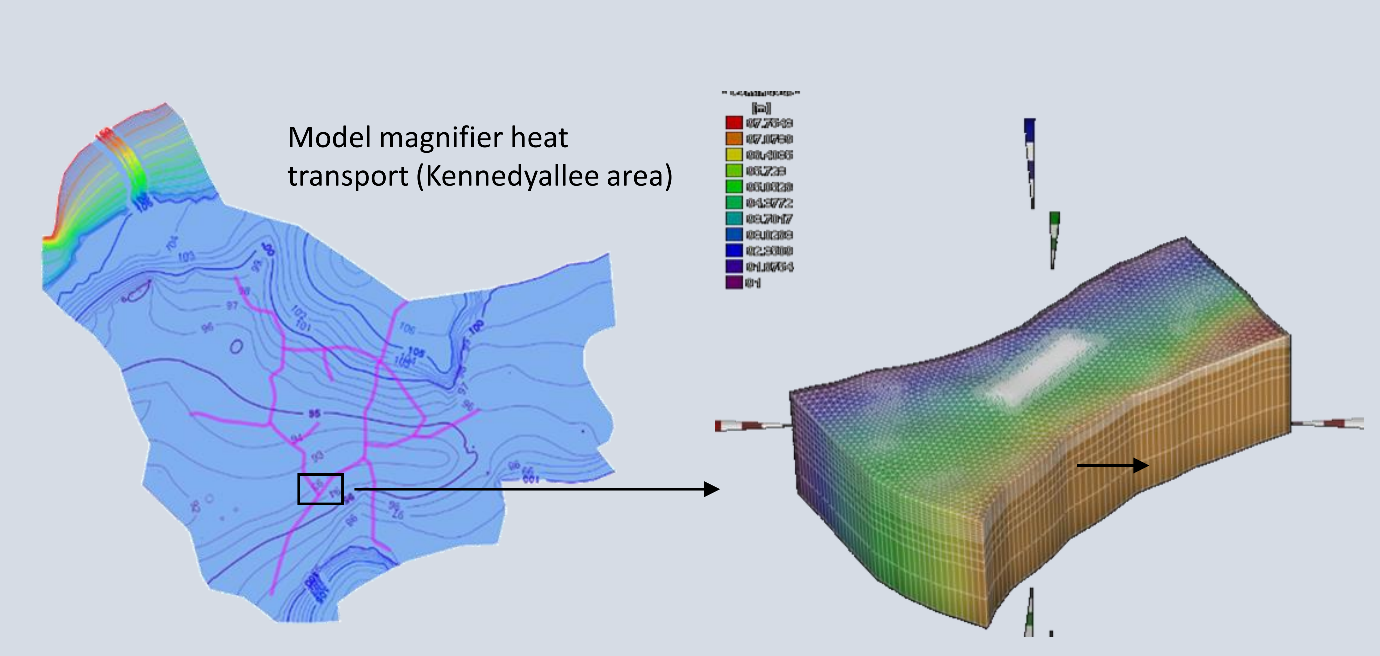
The result of the calculation: The heat extraction (W) of a 20 m pile was between 885 and 1148 W in the scenario calculation for the Frankfurt bridges. Accordingly, an average heat extraction of 1000 W or 1 kW was applied per pile.

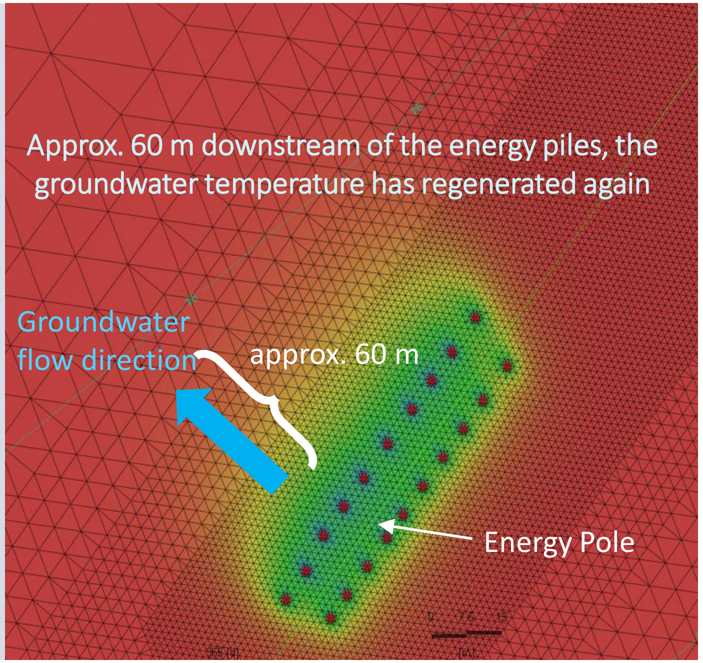
Layer thickness (m)	Lithology	Thermal conductivity λ (W/mK)	Specific heat extraction per m (W/m) for 1800 h		Heat extraction (W) per 1800 h/a	
			from	to	from	to
2,5	Quaternary unsaturated gravel	0,5	25	25	62,5	62,5
7	Quaternary saturated sand	1,7	65	80	455	560
10,5	Tertiary saturated sand and clay	1,4	35	50	367,5	525
				Total	885	1.147,5



Sketch energy pile

It is important in the analysis to estimate the evolution of groundwater temperature downstream of energy piles





Not all sections can be geothermally utilized at the same time, since the energy piles influence each other, especially if they are located in the direction of groundwater flow

The total distance (approx. 60 km) is therefore divided into two simplified sections:

Sections A: Sections in the direction of groundwater flow - these have a reduced energy potential.

Route sections B: all other route sections - these can exploit the geothermal energy potential.

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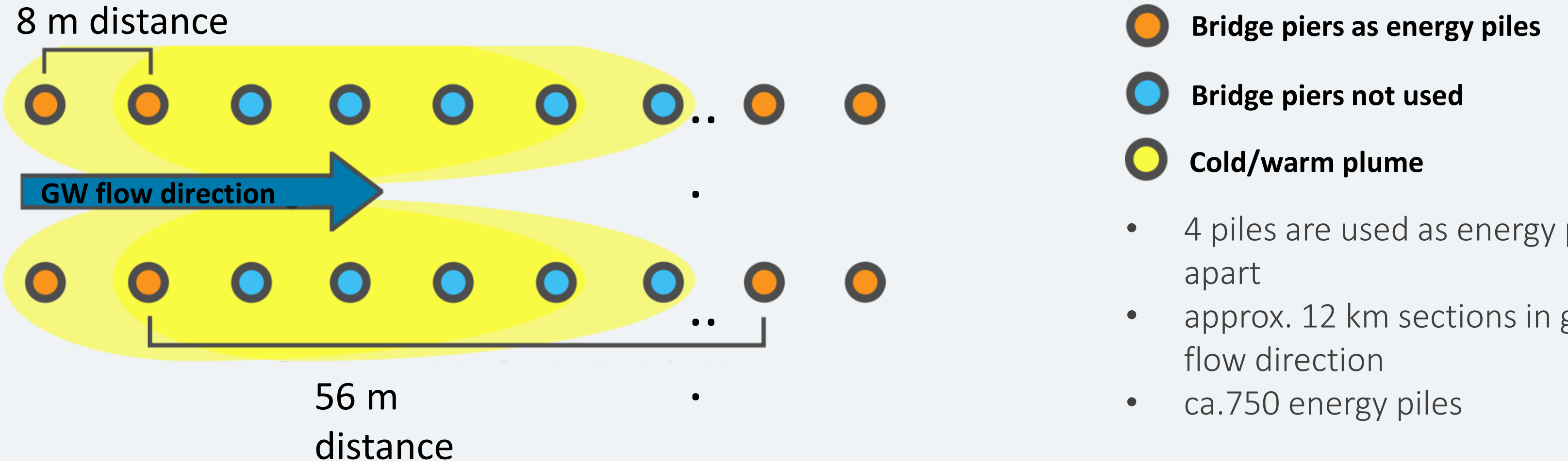
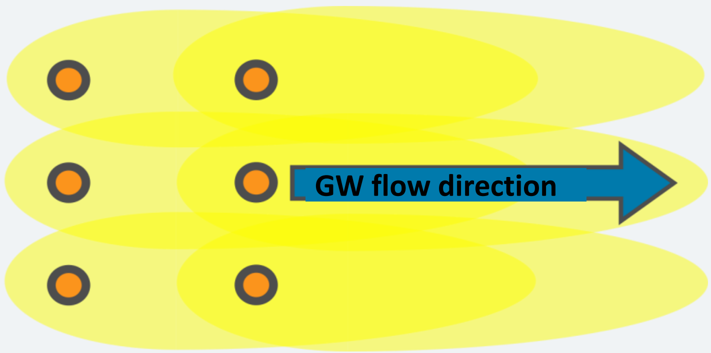
Whether there is a mutual influence of the energy piles depends on the groundwater flow direction

1. section A: sections in groundwater flow direction



- 4 piles are used as energy piles, each 64 m apart
- approx. 12 km sections in groundwater flow direction
- ca.750 energy piles

2. line section B: all other line sections



- All piles are used as energy piles
- approx. 48 km section with different groundwater flow direction
- approx. 12,000 energy piles

Effect of groundwater flow direction on the totality of the column energy piles of the Frankfurt bridges.

The bridge section, which is about 60 km long, is supported by about 15,000 columns, 12,750 of which are equipped with geothermal piles. Since of the 8,760 hours that the year has, only one third of the time (2,700 hours) the geothermal pile system is in use, almost all of the piles are used with a time lag.

Groundwater level
Groundwater flow direction
Routes outside the groundwater model

Section A: reduced heat use (affects all sections with orientation in groundwater flow direction):

- approx. 12 km
- concerns: about 750 piles
- concerns approx. **2 GWh/a** heat extraction

Section B: unaffected by heat flow (applies to all other sections)

- approx. 48 km
- concerns about 12,000 piles
- concerns approx. **33 GWh/a** heat extraction

total heat extraction: approx. 35 GWh/a

Regeneration: Especially in summer -but also during intense sunny days in winter- excess heat must be sent into the soil so that it does not cool down over the years

Some communities have already made the painful experience: If one permanently only gets heat from the earth through near-surface geothermal energy to heat houses, without also sending heat back down, then the ground cools down over the years.

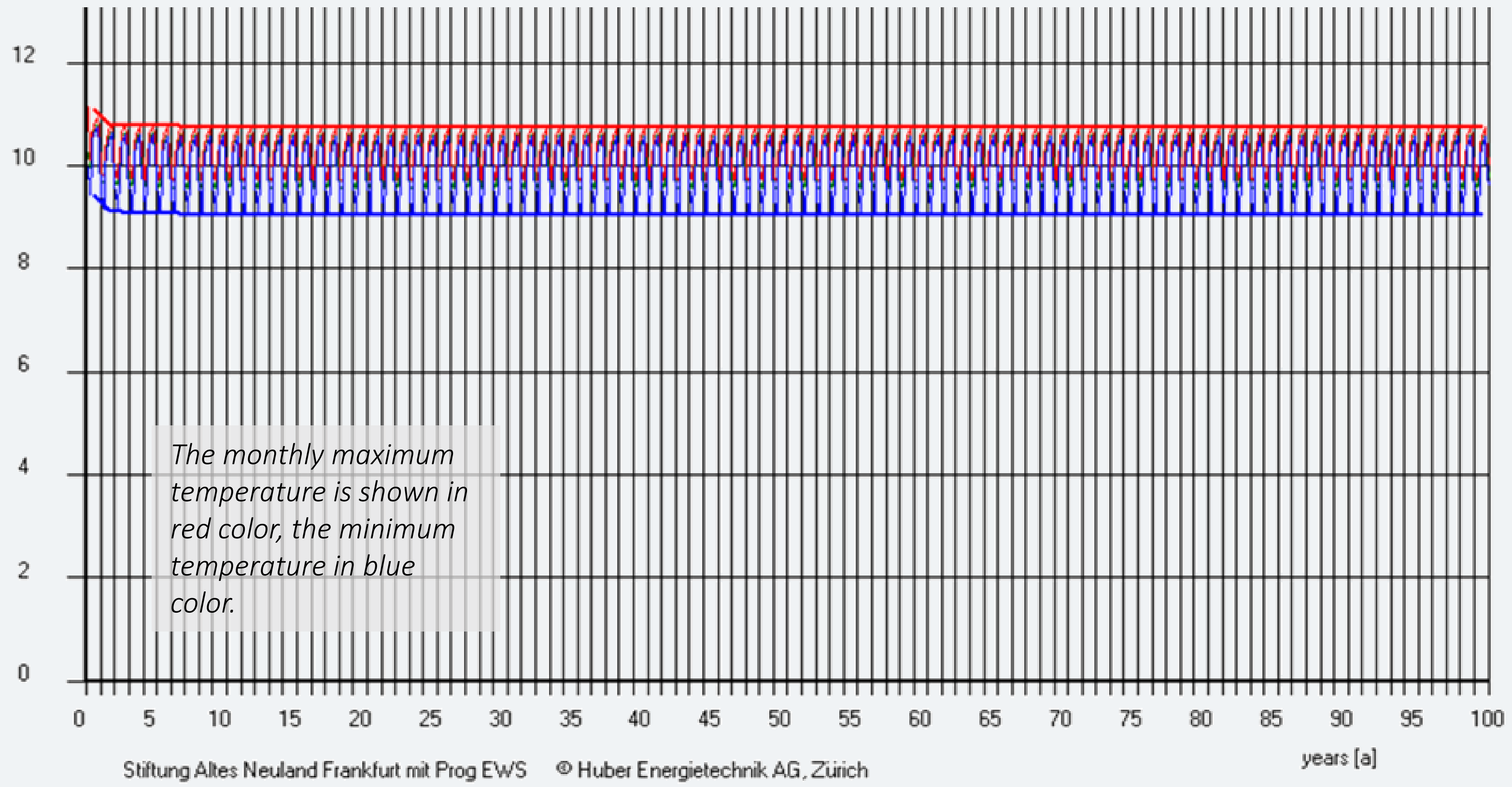
So, in the first of many winters, heat could be extracted from the ground in Frankfurt: The ground and groundwater in Frankfurt have an average temperature of about 12 - 14 °C. Already in the next winter, however, the soil temperature would be slightly lower at the point of heat extraction. Over several years, the effect adds up to a temperature loss of several degrees Celsius. Therefore, the soil must be "regenerated" every summer, which means that heat must be sent down into the soil again.

In the case of the Frankfurt bridges, two heat sources are used for regeneration: 1) the residential cooling of the bridge buildings in summer and 2) the heat from the PVT (photovoltaic thermal collectors) modules. Through these so-called "coupling systems", the ground temperature is restored as the heated fluid flowing down from above through the probes releases heat to surrounding soil.

Coupling system ensures that the ground temperature remains almost the same despite decades of use - example simulation for Kennedyallee in Frankfurt

As part of the present feasibility study, the development of the probe inlet temperature over 100 years was simulated for a section of the Frankfurt bridges at Kennedy-Allee, using coupling systems that provide for the regeneration of the ground temperature.

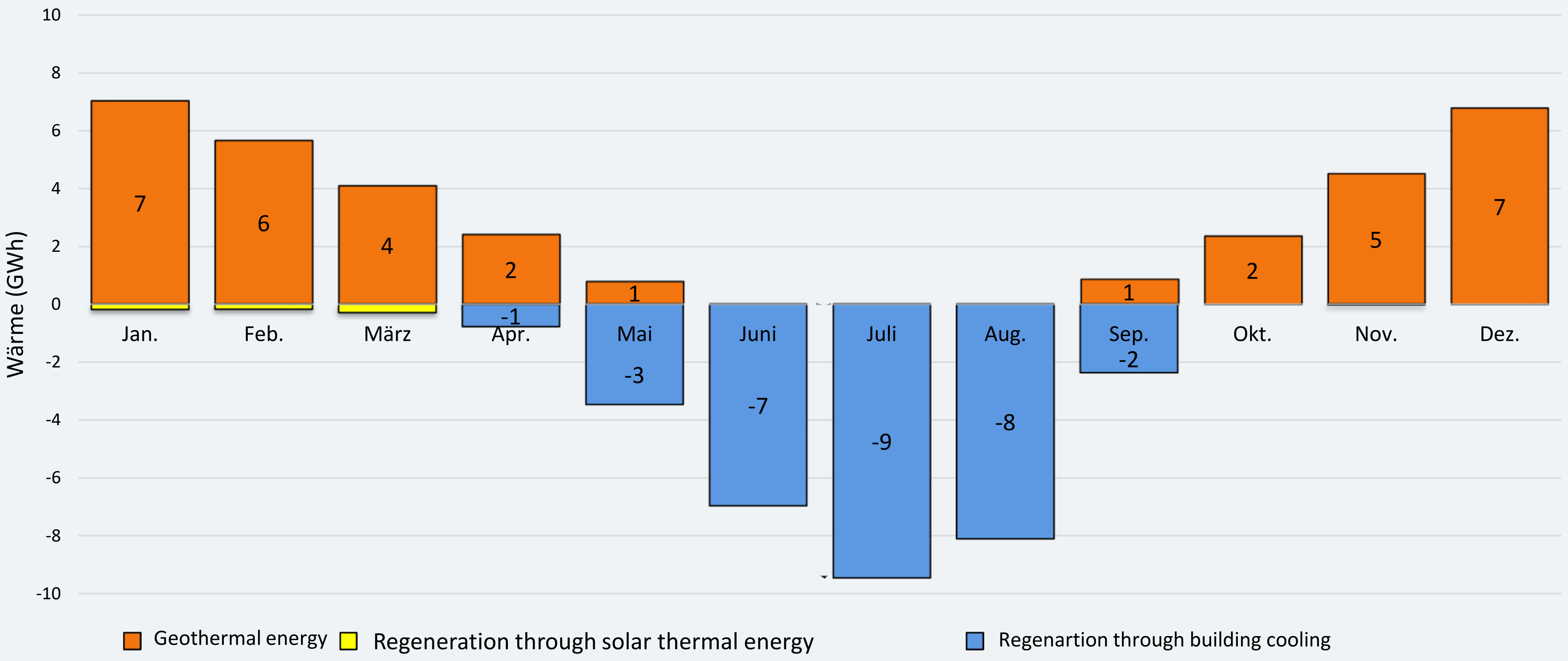
The result confirms the effectiveness of coupling systems: The highest probe inlet temperature occurs only in the first year (11.1 °C) and decreases slightly by the 100th year (10.8 °C). The lowest probe inlet temperature is 9.4 °C in the first year and drops to 9.1 °C by the 100th year.



The monthly maximum temperature is shown in red color, the minimum temperature in blue color.

Of the 35 GWh/a of geothermal energy that helps heat the bridge buildings, 40 percent is extracted from the ground in just two months, from December to January

A large part of the regeneration is realized by the heat of the building cooling in summer; only a small part of the regeneration is realized by solar thermal energy on sunny days in winter



Case 2: Heat collected above ground is sent into the ground via grouped geothermal probes, stored there and extracted from there as needed for heating.

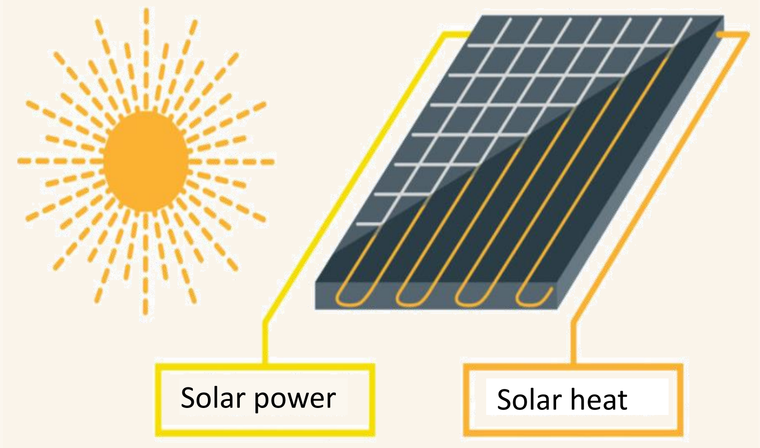
Where the Frankfurt bridges are being built, the pavement of the roads beneath them will have to be renewed as part of the construction project. This opportunity will be used to place probe fields in along the roadway.

These probes reach down to a depth of 250 meters. They are well insulated for the first 20 meters, where they would potentially pass through groundwater-bearing strata and give off their heat prematurely or heat up the groundwater. On the remaining meters, they then release the heat to the surrounding earth for storage.

The heat is collected above ground by hybrid collectors. These generate both: electricity and thermal energy

PVT hybrid collectors (PVT: Photovoltaic-Thermal hybrid solar collector) generate electricity and heat simultaneously. In PVT hybrid collectors, there is a thermal collector on the back of the PV modules, which absorbs the heat from the sun's rays and transfers it to a heat exchanger. Sometimes you can still find both functions - photovoltaic and thermal collectors - mounted separately on roofs.

Photovoltaics and solar thermal collectors combined in one hybrid collector



At the Frankfurt bridges, PVT hybrid collectors are located on roofs, canopies, the sides of the bridge body and on the facades of the bridge buildings. In addition, the parking lots next to the bridges are covered and equipped with PVT hybrid collectors at the expense of the bridge company.

A total of approx. 303 GWh/a of heat is generated by PVT hybrid collectors

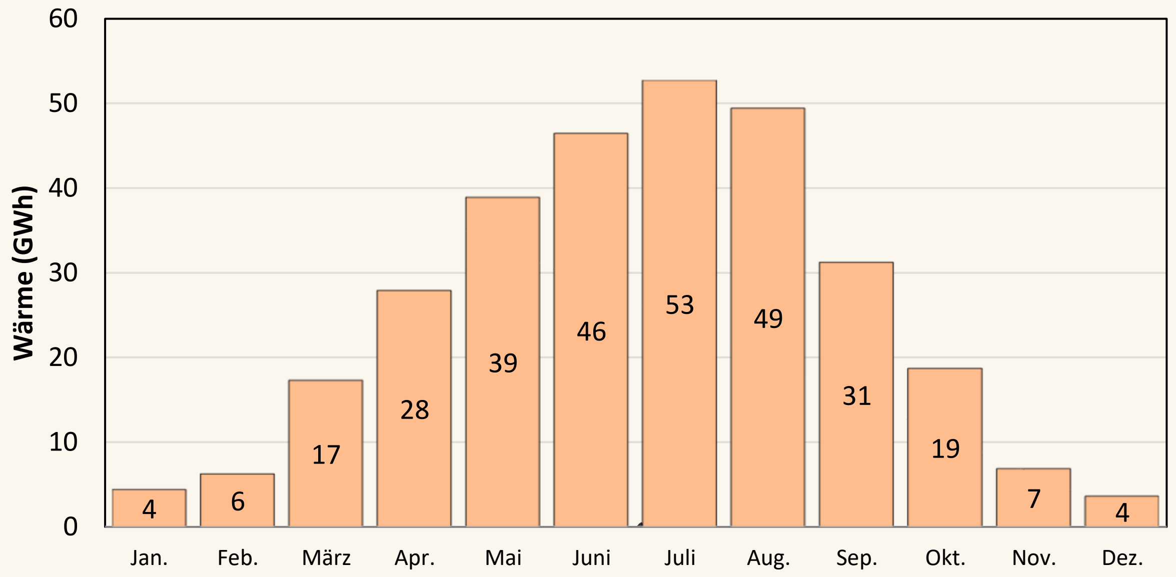
Approximately 303 GWh/a of heat is generated with 1 million square meters of PVT hybrid collectors; about half of this is on the bridges and the other half is on the parking lot canopies adjacent to the bridges.

Thermal energy generation through PVT modules

PVT solar modules	total area (m2)	85% of total energy (GWh/a)	Shares E (%)	Shares on & next to the bridges (%)
(1) Roofs of the bridge buildings	47.429	11,25	3,71	51,56
(2) Canopies and station roofs	58.078	14,17	4,67	
(3) Bridge sides	445.723	119,51	39,39	
(4) Facades of the bridge buildings	55.882	11,51	3,79	
(5) Parking next to the bridges	411.675	146,97	48,44	48,44
SUM	1.018.787	303	100	100

Around 80% of the heat (246 GWh/a) is generated in summer, when there is almost no demand for heat. Therefore, the generated heat is stored underground in BTES (Borehole Thermal Energy Storage) in summer and retrieved in winter for heating with low temperatures.

In winter, the remaining 20% heat (57 GWh/a) is generated. This is passed on directly to the consumer.



Another source of thermal energy: waste heat.
The waste heat potential from data centers, industrial parks and also waste water in Frankfurt amounts to around 190 MW or more than 1.66 TWh per year.

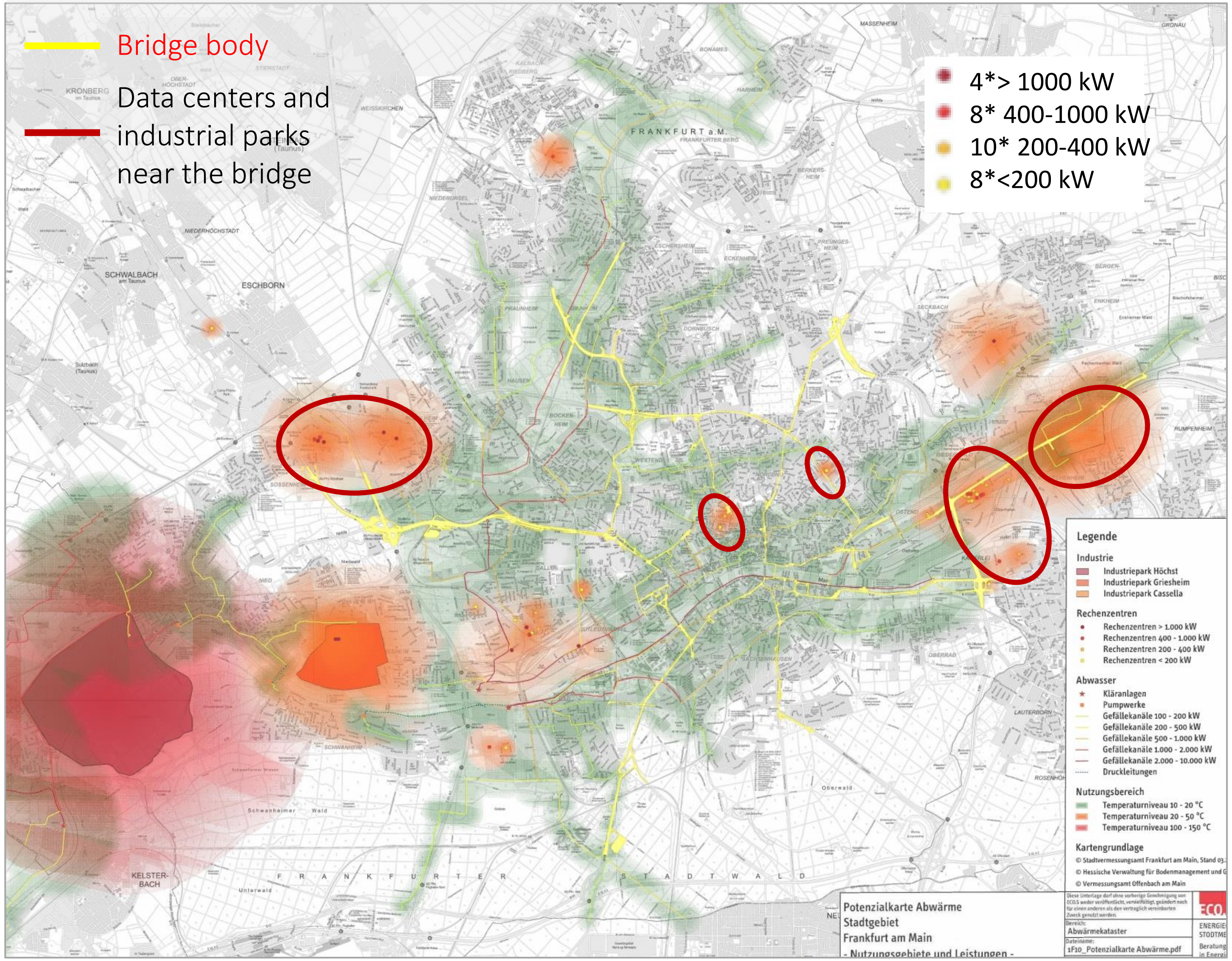
According to the Frankfurt waste heat register, the 1,660 GWh per year are divided as follows:
100 MW (876 GWh) heat from wastewater,
40 MW (350 GWh) waste heat from industrial parks,
50 MW (438 GWh) of waste heat from data centers.
This is about one third of the heat consumption of Frankfurt households, but the thermal heat is only available as low-energy waste heat and would therefore only be usable in buildings with heat pump heating.

Until now, however, the waste heat from the data centers or industrial parks in Frankfurt could not be used at all because there was no pipeline system that could transport the heated brine liquid to the heat exchangers of building users. Unfortunately, it cannot be fed into Mainova's district heating pipeline either, as this is designed for 80 to 90 °C hot liquid.

The construction of the Frankfurt bridges will therefore create a pipeline system along the bridges that not only stores heat collected by PVT hybrid collectors in the ground, but also collects and transfers waste heat from data centers and industrial parks, such as those found primarily along Hanauer Landstrasse and in Sossenheim.

For these data centers and industrial parks, the Frankfurt bridges represent the direct link to the use of their waste heat in buildings or by other consumers.

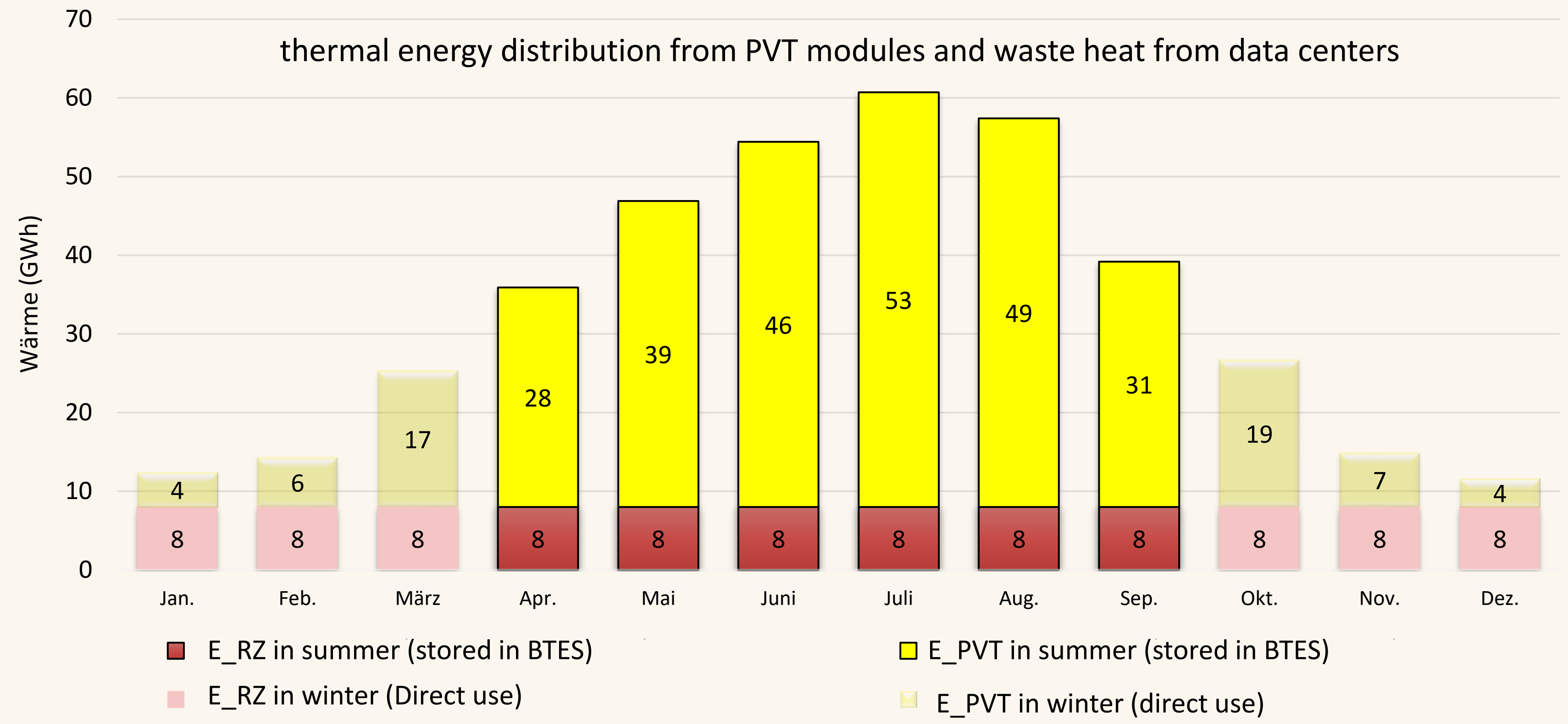
The Frankfurt bridges run past some critical locations where data centers generate an extremely large amount of waste heat - a very useful source of energy, especially on less sunny or warm days in fall or winter



Near the bridge, 30 data centers and the Cassella Industrial Park generate about 200 GWh/a of low-temperature waste heat that currently goes unused. Half of this (100 GWh/a) can be collected and used with the help of the bridges.

Thermal energy is not only available in summer

Approx. 246 GWh/a of low-temperature thermal energy (approx. 35°C) from PVT modules and approx. 50 GWh/a of waste heat from data centers are stored underground from April to September. But also between Jan. and March as well as Oct. and Dec. the generated heat is either fed underground for regeneration or directly transferred to the consumer.



The thermal energy from PBT and RZ collected in summer (approx. 296 GWh/a) is not consumed directly, but stored in long-term storage facilities

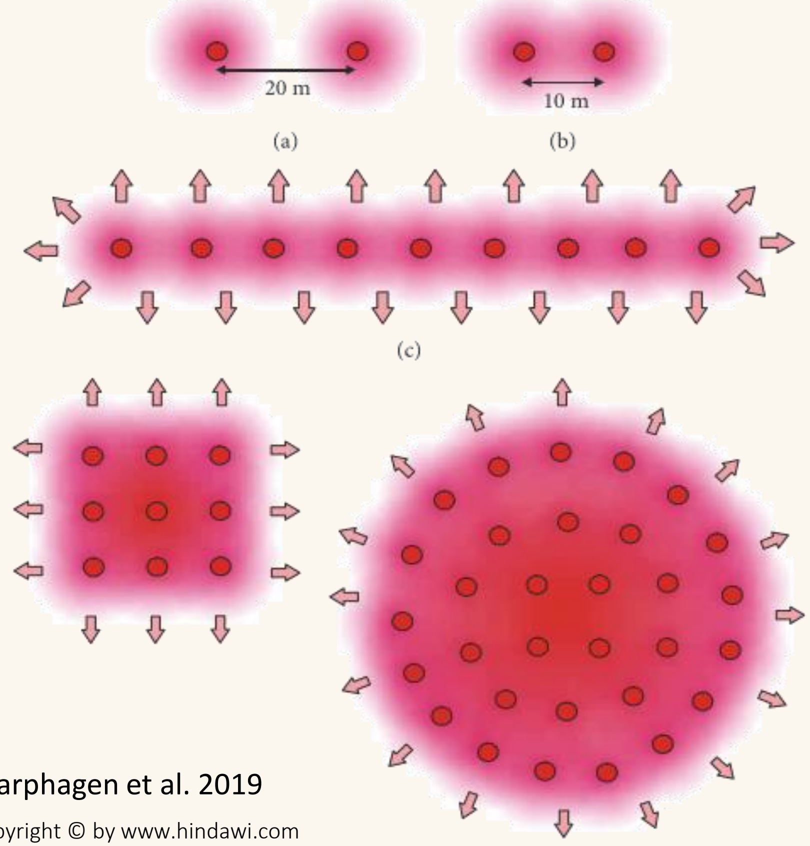
Heat from PVT modules and also waste heat from data centers is stored underground in "probe fields

The Frankfurt bridges offer the possibility of installing probe fields, so-called Borehole Thermal Energy Storages (BTES), at strategically favorable locations, e.g. under the supply centers or roadways beneath the bridges, in order to store - as the name suggests - surplus heat. In this way, time can be bridged between supply (summer) and demand (winter).

The storage efficiency of individual geothermal probes is comparatively low. Therefore, one lays so-called "geothermal probe fields", which arranged in a circle or square most efficiently store the heat. It is recommended to place them at a distance of less than 10 m (optimum 3 to 5 m).

Other factors that are decisive for the efficiency are
thermal properties of the subsoil
groundwater flow rate
surface to volume ratio
working temperatures and time control

Numerical models were built to estimate storage potential and utilization rates, and a long-term simulation of storage operation was performed.

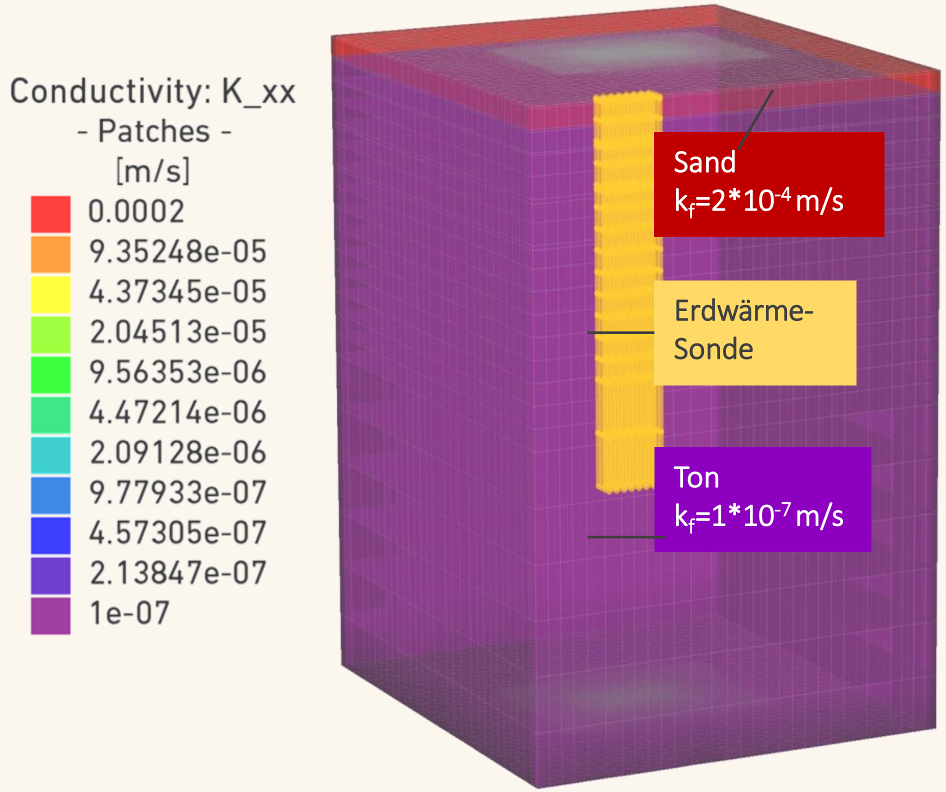


Skarphagen et al. 2019

The Borehole Thermal Energy Storage (BTES) model calculates the stored and extracted thermal energy as well as outlet temperatures per storage cycle - and thus also the storage efficiency of BTES.

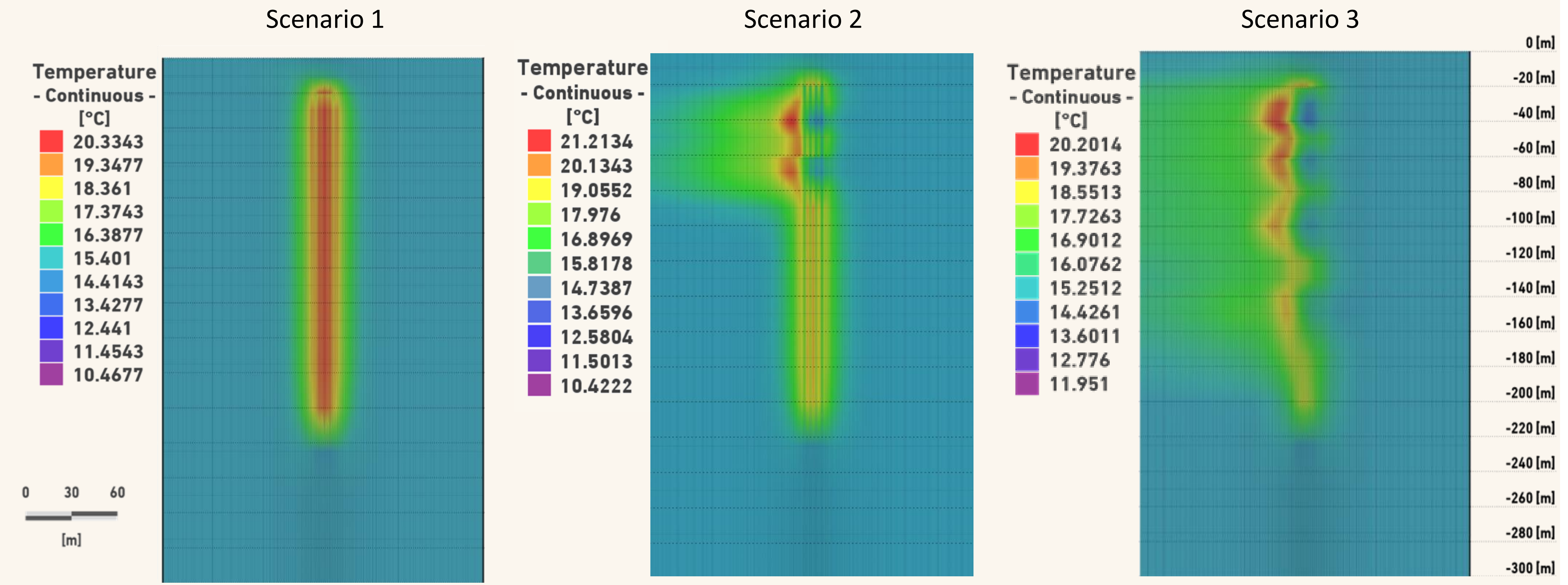
Requirements:
Model with "4 on 8 probes arrangement", i.e. 32 geothermal probes (EWS) with 4 m distance each.
supplied water temperature in summer of 35 °C and in winter of 4 °C
Upper aquifer up to 10 m below ground surface (below ground surface level), then clay
EWS from 20 to 200 m below ground surface (slice 5-23)
Hydraulic gradient of 6.5
EWS implemented as 1D-line element

Geothermal probes of the BTES:
U-probes with standard dimensions
150 mm borehole diameter
32 mm probe diameter
Constant volume flow with 10 m3/d per probe
Simplified approach: without complex interconnection of the EWS, each EWS a single circuit



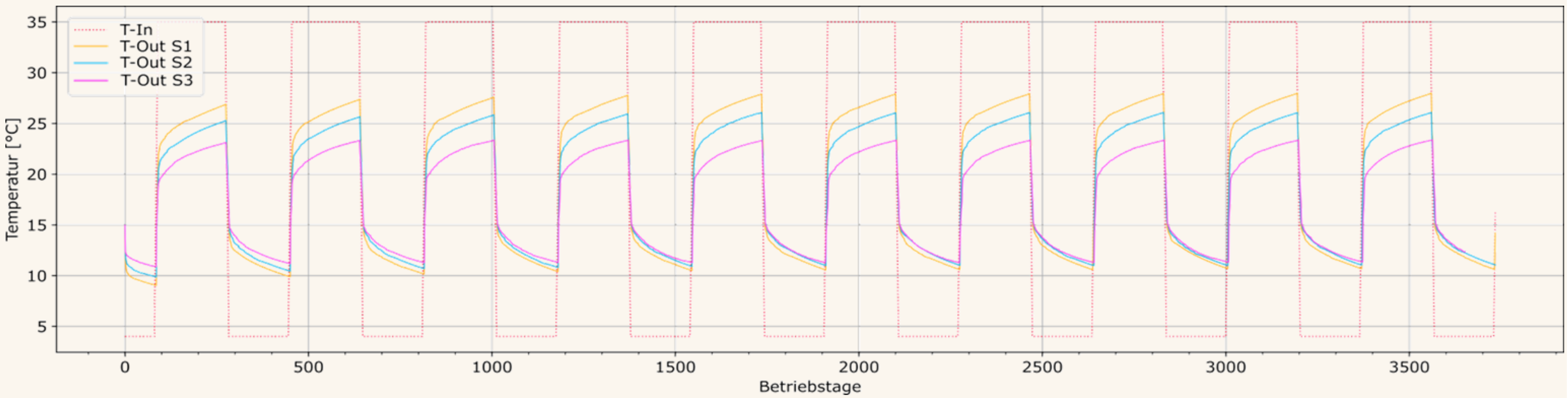
For the estimation of the probe field performance along the Frankfurt bridges, three scenarios were simulated, each with different geological conditions that occur in the Frankfurt area

1. Scenario 1 (S1): Ideal case for storage with completely continuous clay layer with hydraulic permeability of kf =10-7 m/s, thus hardly any convective heat losses due to flowing groundwater.
2. Scenario 2 (S2): Clay interrupted by two sand layers (kf =2*10-4 m/s) with thicknesses of 2 and 8 m, thus increased convective heat losses on 5% of the section
3. Scenario 3 (S3): Clay interrupted by four sand layers (kf =2*10-4 m/s) with a total thickness of 50 m, thus convective losses increased on 25 % of the section



The model results show the inlet and outlet brine temperatures within the 10-year operation period. The inlet temperature (T-In) is set to 4 °C in winter and 35 °C (outlet temperature of the PVT hybrid collectors) in summer for all scenarios. For all scenarios, it can be seen that the outlet temperature (T-Out) decreases during heat supply (in winter) and increases during storage (in summer).

Model results from different scenarios: In & Out Temperatures in EWS
Outlet temperatures are lower with increasing convective losses in the storage phases
In the withdrawal phases the outlet temperatures are very similar



Why does the simulation show similar outlet temperatures in winter? Although the temperature gradient to the storage volume is higher for S1 (only clay) compared to S3 (a lot of sand) because the stored heat was not transported away from the groundwater, the heat exchange between the borehole heat exchangers and the storage volume is nevertheless lower at the same time because there is hardly any convective heat transport.

In all scenarios for the probe fields along the Frankfurt bridges, the extracted heat increases after the first few years and reaches a plateau, while the amount of stored energy shows a reverse trend

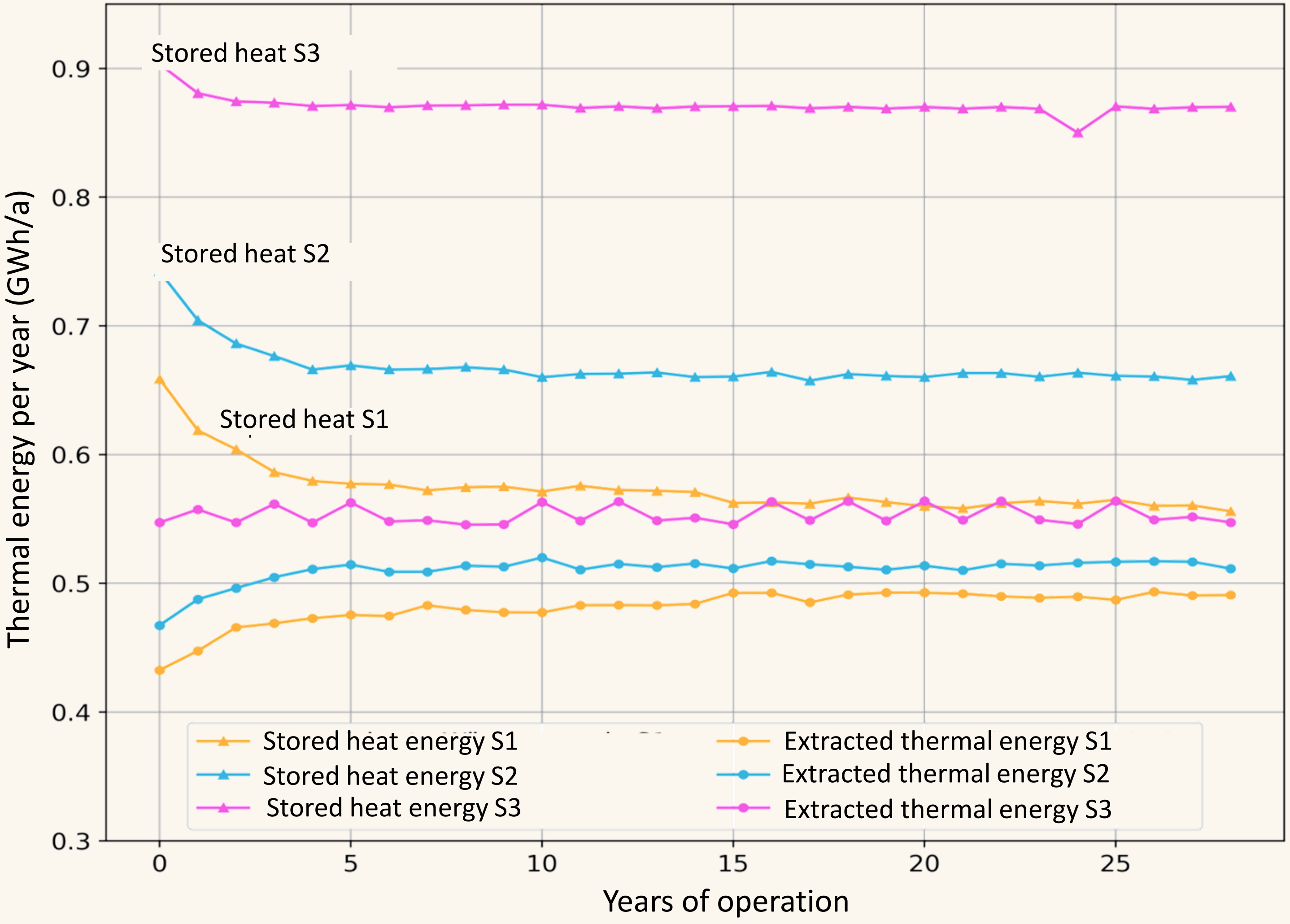
The model results show the stored and extracted thermal energy over an operating period of approximately 30 years.

In the scenarios with groundwater flow, slightly more energy can be extracted, but significantly more is put in as well

Storage utilization rate:
S1: ~ 87 %
S2: ~ 78 %
S3: ~ 63 %

Convective losses have a significant effect on the storage efficiency.

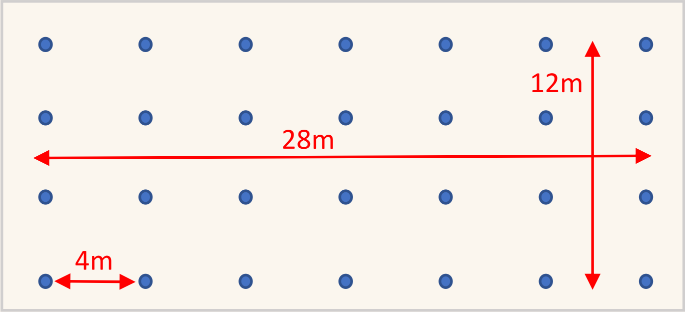
The storage efficiency is significantly lower if circuitry and control etc. are taken into account.



Geothermal probe fields will require 175,000 m2 of space: They will be installed either (I) under each utility center, (II) next to the data centers and industrial park, and (III) along the bridges in the course of bridge construction under the roads

According to the simulated model, 32 borehole heat exchangers (12*28 = 336 m2) store 650 MWh of thermal energy. In order to store 296 GWh/a, approx. 455 groups with 32 borehole heat exchangers or approx. 155,000 m2 area are required.

650 MWh
Storage volume
per probe field



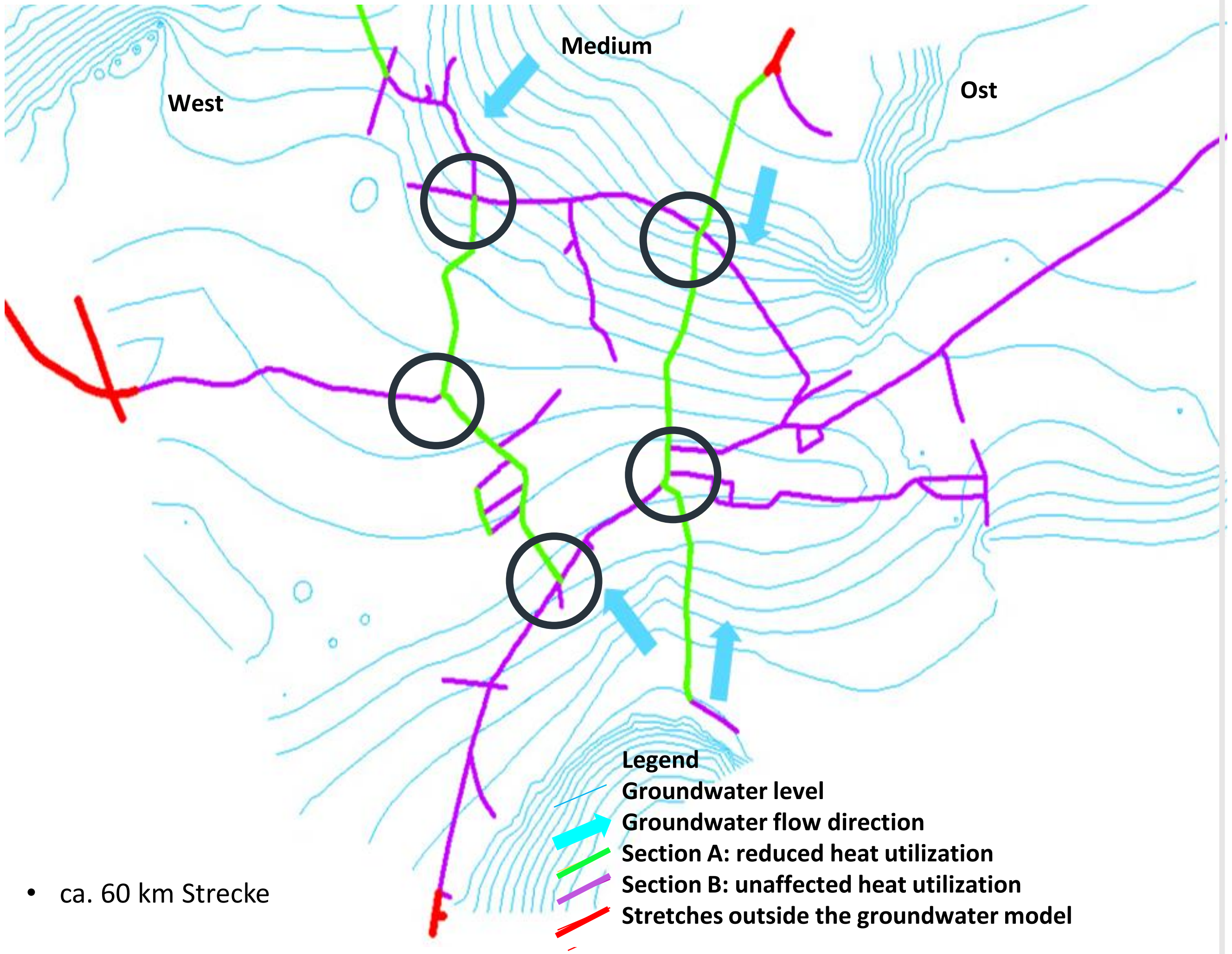
336 m2
Area required
per probe field

(I) Geothermal probes can be installed under each supply center. There are 200 supply centers with an average surface area of 100 m2, so that in this way 20,000 m2 of surface area can be equipped with borehole heat exchangers already during the construction of the supply centers.

(II) In addition to the data centers and the Cassella Industrial Park, another 5,000 m2 of geothermal probes can be installed to store the heat collected from the east arm and the west arm of the Frankfurt bridges.

(III) The remaining 130,000 m2 of space required will be along the 60 km long route of the Frankfurt bridges: During their construction, the pavement of the overbuilt roads will have to be renewed in large parts anyway. Here, all the necessary geothermal probe fields can be installed on 130,000 m2.

Moreover, the 130,000 m2 area for the probe fields should, if possible, be laid out around the crossing areas of the bridge sections, as this is more favorable from an energy point of view: from there, the heat has shorter distances to the point of origin and also to the point of use.



The two sections A (which are in groundwater flow direction: green lines) divide the bridge landscape into three areas: East, Middle, and West.

The placement of the geothermal probe fields is most sensibly done around the intersections of the bridge courses (indicated by black circles):
This is because if heat only ever needs to be routed to the next intersection for storage (and vice versa for extraction), then the route length for energy transport is shortened, heat losses are lower, and the efficiency of heat storage is thus higher.

Of the 15,000 columns on the bridges, the piles on 12,750 are fitted with probes. Like the probe fields under the roads, these are connected to an underground ring main so that heat can be passed on when it is not needed on site

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Approximately one to two meters below ground, i.e. in the frost-free zone, a ring line runs to which both the probes in the column piles and the geothermal probe fields under the roads are connected. These particularly well-insulated connecting lines allow the heated probe fluid to flow wherever it is needed. The customers are the buildings on the bridges, greenhouses and swimming pools next to the bridges and, in the more distant future, residential and office buildings next to the bridges.

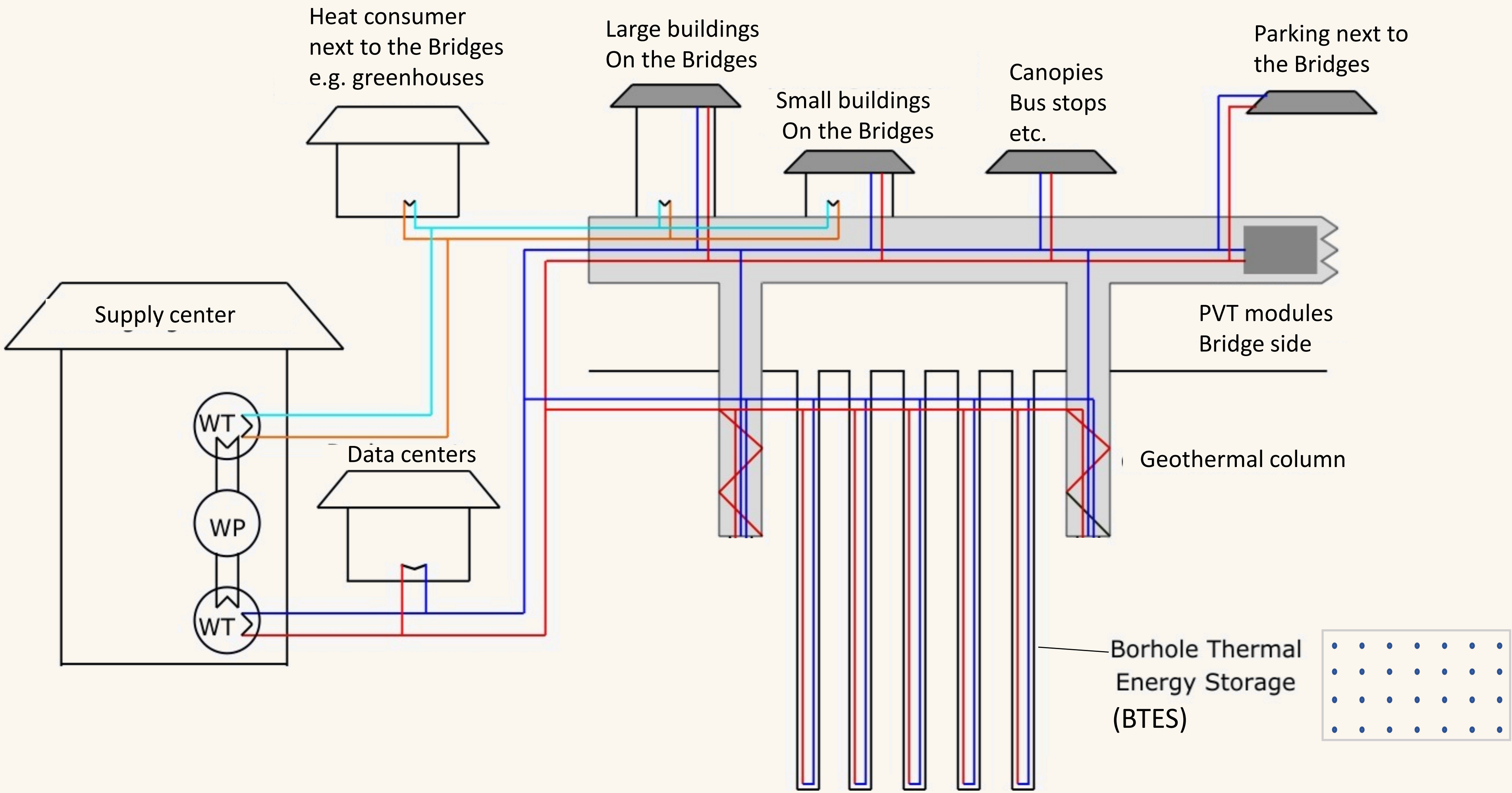
When heat is extracted from the storage tanks, the temperature-controlled probe fluid is piped up from the ground when heating is required and -just like the brine from the PVT modules- is piped underground to the basement of the nearest supply center.

The brine from the solar thermal energy of the photovoltaic modules runs through pipes along the columns down to the ground, where it continues to flow in a common connecting pipe to the supply center.

Either it is used there (in winter) for heating or it is transferred to the ground for storage, to be brought up again when needed and directed to the supply centers. There, the heat is transferred through a heat exchanger to the pipes that continue to the bridge buildings and other consumers for heating.

Also, the probe fluid from the ground, which was heated by the ground temperature there of about 14 °C in the bridge pier probes, comes up in the bridge piers to the geothermal ring main, which is about 2 m below ground level, so that it is frost-free and comes out at the level of the basement of the utility center to be used there.

Both the pillars that will be equipped with probes ("geothermal pillars") and the probe fields (BTES) are connected to the common heat conduction network of the Frankfurt bridges, which requires a good control and regulation system



If one day fewer lanes are needed and buildings are constructed under the Frankfurt bridges, these can also be supplied geothermally

Since almost all supports of the bridges are geothermally activated, any additional "buildings" that may be constructed in the future next to or under the bridges can also be heated in an energy-efficient manner. Due to the supply centers connected to the system, which are planned every few hundred meters along the bridge, the connection of these additional buildings is unproblematic.

Frankfurt's bridges not only create green and humane living spaces above ground, but their columns also open up the possibility of using the ground beneath the city as an energy store underground

Almost 1 million m2 of solar thermal area is being created on Frankfurt's bridges, not only on the roofs of the bridge buildings, but also on the body of the bridge and on the parking lots along the bridges. With the heat from this, as well as the waste heat from many data centers, the ground under the bridges can not only be regenerated after the winter season with its heat extraction; in fact, far more heat could be sent down than taken out. Theoretically.

Because there is one limiting factor: the groundwater must not get too warm. In some places in downtown Frankfurt, it is already 18 °C or more due to the geothermal energy from the high-rise buildings. These are already problematic values: Too much warming of the groundwater can be harmful to several hundred animal species that inhabit this area and to the ecosystem of groundwater organisms that make an enormous contribution to purifying the groundwater.

Accordingly, during the preliminary planning phase of the Frankfurt Bridges, it must be examined in detail together with the Hessian State Office for Nature Conservation, Environment and Geology to what extent and at which points the Frankfurt Bridges geothermal system may store heat in the ground.

Conclusion: The bridge structure and bridge construction can be used to extract heat from the ground or store it there

At present, infrastructure projects are usually still considered to be environmentally harmful and, due to the CO_2 emissions of concrete buildings, also to be harmful to the climate.

This contrast between structure and nature can be eliminated if the structure itself is used for energy generation and storage or if environmentally friendly renewable energy generation is installed at the same time as the infrastructure is built.

In the case of the Frankfurt bridges, the pillars can be used for energy generation from the ground; furthermore, the construction project itself can be used to install probe fields for energy storage along the bridges in the course of bridge construction.

Old New Territory
Frankfurt

THE PLAN

BUILDINGS & BRIDGES
URBAN GREEN & NATURE
WATER

ENERGY
The urban energy transition
Power requirement of the bridges
Heating and cooling demand
Photovoltaics as quarter power
Near-surface geothermal energy
Energy infrastructure of the future

TRANSPORT
URBAN CLIMATE - GLOBAL CLIMATE

ART & CULTURE
PACKAGING - INNOVATIVE
OLD NEW TERRITORY WORLDWIDE

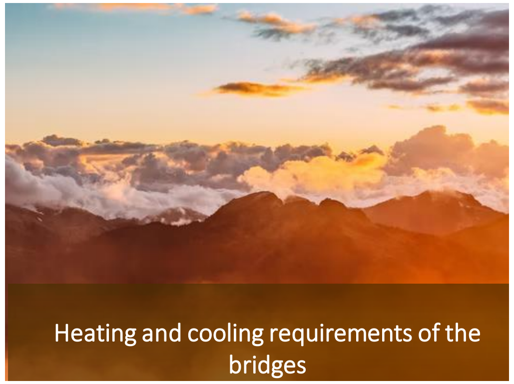
LAW
FINANCES
IMPLEMENTATION

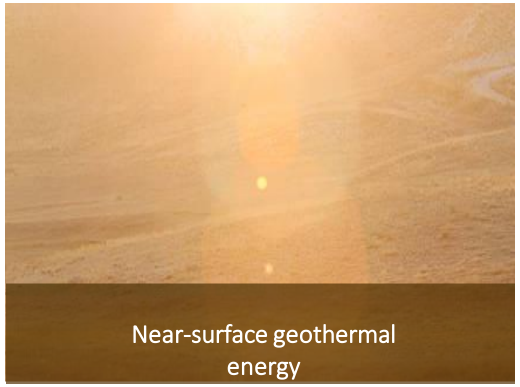
SPECIALIST INFORMATION

SEARCH
THE TEAM
CONTACT & IMPRINT


Electricity demand on the Frankfurt bridges


Photovoltaics as quarter power


Heating and cooling requirements of the bridges


Near-surface geothermal energy


The energy infrastructure of the future


The bridge world


Sustainability through technology


The Co2 balance of bridges

EMPLOYEES

Architecture
Image & photo
Bridges
Energy

Geoinformation
Green & Nature
Communication
Art & Culture

Urban climate - world climate
Statics
Transportation
Technology & IT

Water
Packing
Webpage & Design

Law
Finance
Implementation

Critical sparring partners:
Professors
Professionals
Inspirers & Supporters

Die Energie-Infrastruktur der Zukunft

The Frankfurt bridges represent the infrastructure of the future: with their help, energy is generated decentrally and they provide volatility compensation through on-site consumption as well as a sophisticated storage landscape

The energy generated by the bridges is partly in the form of electricity and partly in the form of heat. In the infrastructure of the future, both energy flows are controlled and optimized in their interaction. To this end, a sophisticated control system is being created for Frankfurt's bridges, which is exemplary for the city quarters of the future.

Chapter content: managing the renewable energy landscape for a smart city neighborhood like Frankfurt Bridges.

Energy sources and energy consumers are shown in their interaction on the Frankfurt bridges.

Due to the collection of surplus energy, which the Frankfurt bridges enable both thermally and electrically, the bridges themselves have a high degree of self-sufficiency and can supply the rest of the city with energy. The prerequisite for this is a storage system that bridges the short-term bottlenecks with a battery landscape (nights, days with little sun) and can also provide long-term storage for the winter months with hydrogen storage and geothermal probe fields.

In addition, the bridges will establish a grid system that can receive decentralized energy and transport it either to the nearest consumer or to the nearest available storage facility.

Historically, most energy in cities and towns is generated continuously and centrally

Large energy producers, such as coal or gas-fired power plants, generate electricity that is then transmitted to the end consumer via a distribution network. This also makes sense for nuclear, coal or gas-fired power plants, and even for wind farms: decentralized power generation in one's own home was unthinkable until the spread of photovoltaics - or outdated, since not everyone lights a fire on their own stove or has a mill wheel driven by the stream behind their house.

Accordingly, the distribution networks of cities are not designed not only to distribute electricity, but also to permanently collect it in a decentralized manner.

The challenge: generation of renewable energy is mostly decentralized and, moreover, extremely volatile

In central power plants with combustion technology, the amount of energy generated can be regulated higher or lower depending on demand, especially in the case of gas-fired power plants. In the case of photovoltaics, the amount of energy generated is irregular depending on the time of day, season or weather.

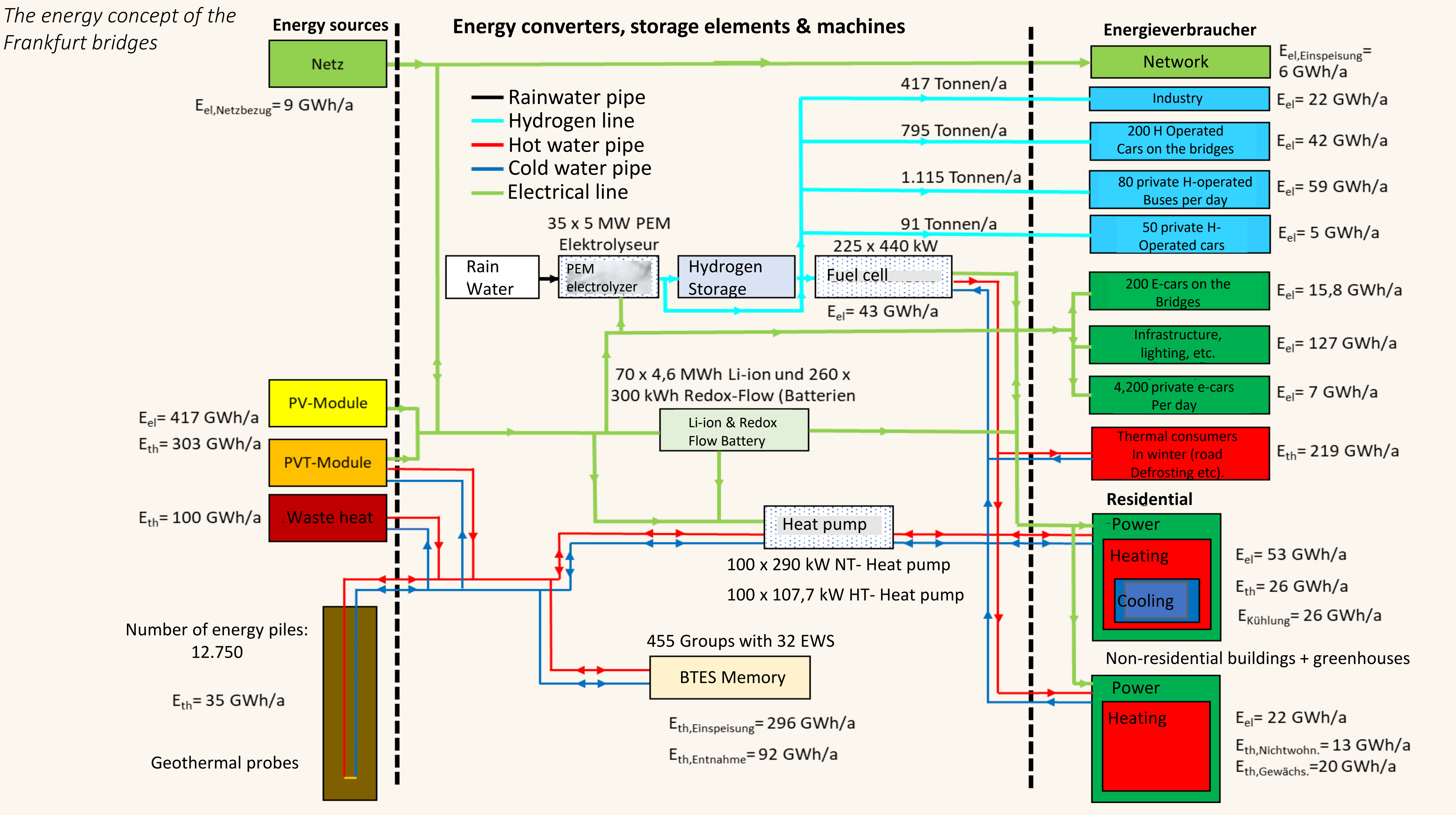
For the CO2-neutral city of the future, the lack of controllability and predictability means that electrical energy must be stored in large quantities by means of buffer storage so that it is available to the end consumer at all times.

The smart city of the future will have to cope with two tasks: creating a grid structure for decentrally generated energy and controlling the energy supply in the event of volatile energy volumes - this has been modeled for the bridges as an example

Old New Territory Frankfurt

In the infrastructure of the future, smart cities - like the Frankfurt bridges - will establish interdisciplinary controlling for the complex interplay of decentrally and volatile generated energy

The energy concept of the Frankfurt bridges



For the Frankfurt bridges, the three areas "energy sources, energy conversion and storage, and energy consumers" have been included in the overall simulation

The energy concept of the Frankfurt bridges has been simulated using Polysun

Energy sources:

PV modules: in 8 directions (south, south-west, west, etc.) with angles of 0, 37 and 90 degrees.

PVT modules: in south direction with optimal angle

Geothermal probes: for space heating

Energy source: representing waste heat from data centers.

Grid: If the power demand is high, the grid power is consumed (if vice versa, the grid is an energy consumer)

Energy storage:

Li-ion batteries: 320 MWh storage capacity.

Redox flow batteries: 80 MWh storage capacity

Geothermal probes: as BTES storage

Energy consumers:

Eectrical consumers: for residential and non-residential buildings, bridge infrastructure (lighting, irrigation, etc.), electric vehicles, hydrogen production

Swimming pools: as thermal consumers

Buildings: for space heating of residential and non-residential buildings and greenhouses

Energy sink, source: representing the residential buildings during space cooling.

Facilities:

Heat pumps: for space heating and cooling

Combined heat and power plant: as fuel cells for the purpose of back-up for increased energy demand in winter

Control: controlling of the whole systems

Parameters, boundary conditions and prerequisites for modeling the energy concept of the Frankfurt bridges

In order not to make the very complex simulation too complex, it has been carried out for 1% of the total energy of the bridges as a representative subsection for 100% of the energy. Therefore, the simulation is performed accordingly with only two supply centers, instead of the 200 supply centers that exist at the Frankfurt bridges.
The simulation time steps are 1 hour each, over the period of one year. The simulation lead time is used with 270 days to more accurately simulate storage effects for the BTES.

High temperature heat pumps coupled with data center waste heat and solar heat are used, while low temperature heat pumps are used for coupling with geothermal heat.

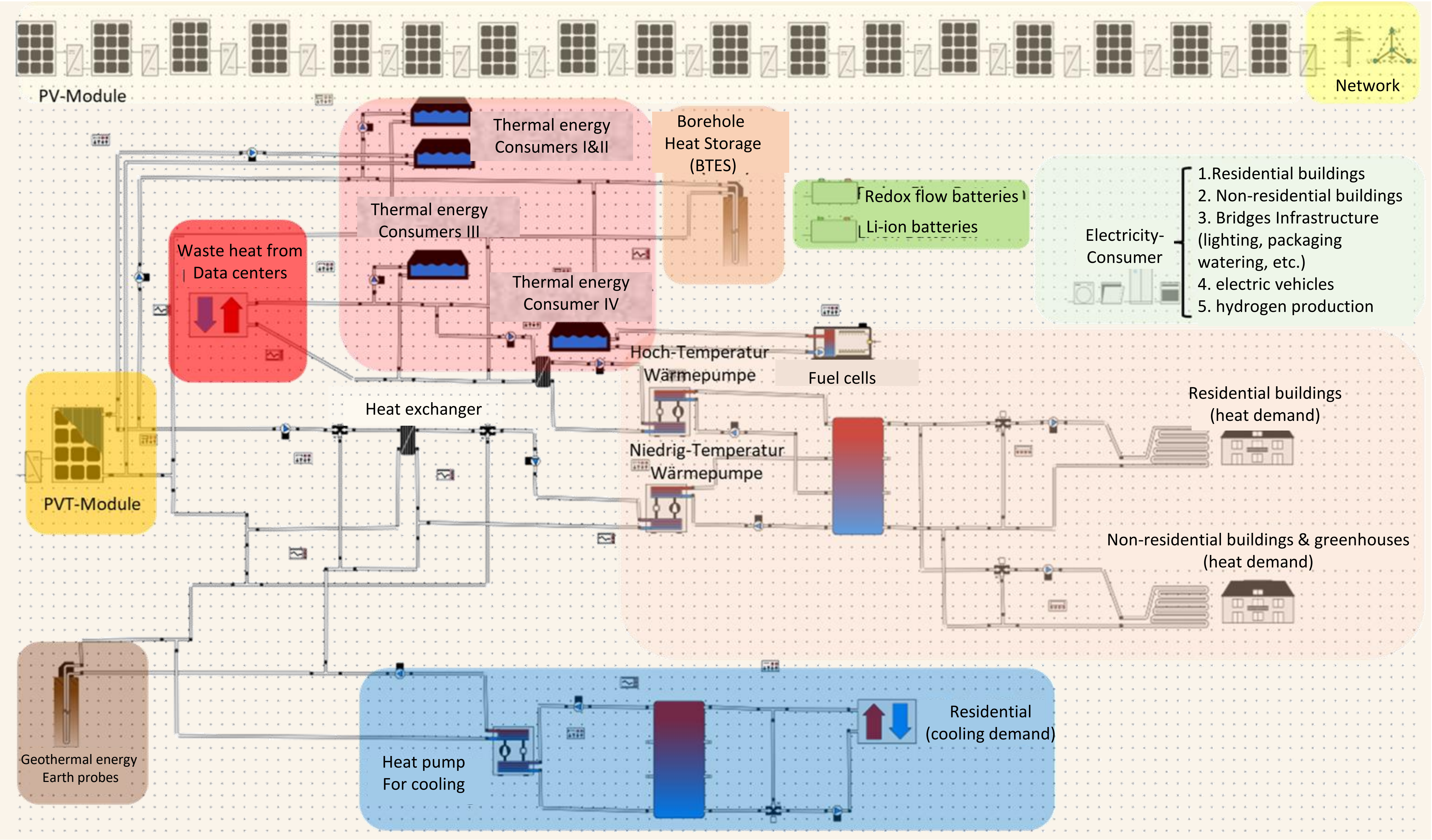
Heat from PVT modules and waste heat from data centers is stored in the BTES from Apr. to Sep. and extracted or consumed from Oct. to March.

In order to use heat from fuel cells more efficiently, the fuel cells are only in operation in winter when energy demand is high.

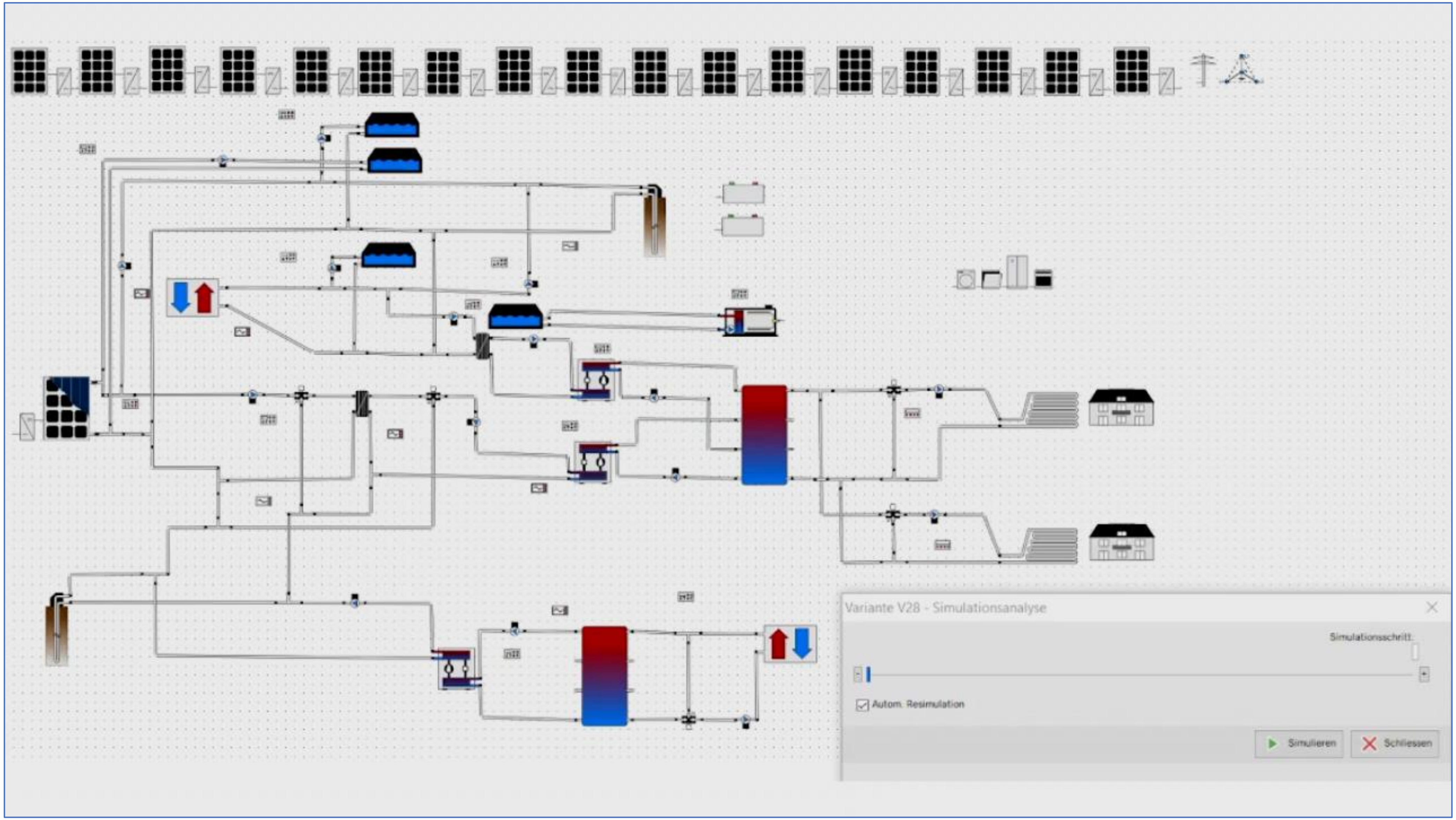
The swimming pools are mentioned as exemplary thermal energy consumers, since a multiple of the bridge consumption of thermal energy is generated or stored and buyers must be found for this, so that the stored heat does not accumulate in the ground over the years and heat it up as well as the groundwater. In the distant future, however, when the buildings along the bridges have gone through renovation cycles, this heat can then be directed to heat pumps in those buildings.

In summer, heat from cooling ceilings in the roofs of the residential buildings is sent down into the ground for regeneration. In winter, some of the excess thermal energy from PVT modules is also sent into the ground for regeneration, but only in a temperature-controlled manner when the brine temperature of the PVT modules is lower than 30 °C, since the geothermal storage tanks in the column piles (unlike the much deeper-reaching probe fields) are not allowed to heat up the ground and groundwater excessively, but only supply heat there for regeneration purposes.

The modeling of the energy concept for the Frankfurt bridges took into account electrical and thermal components



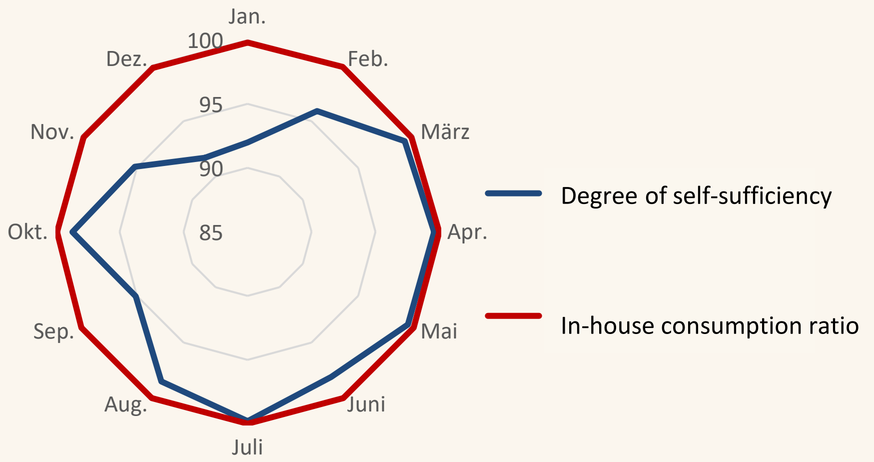
In order to make reliable statements, a simulation was performed on an hourly basis for the period of one year

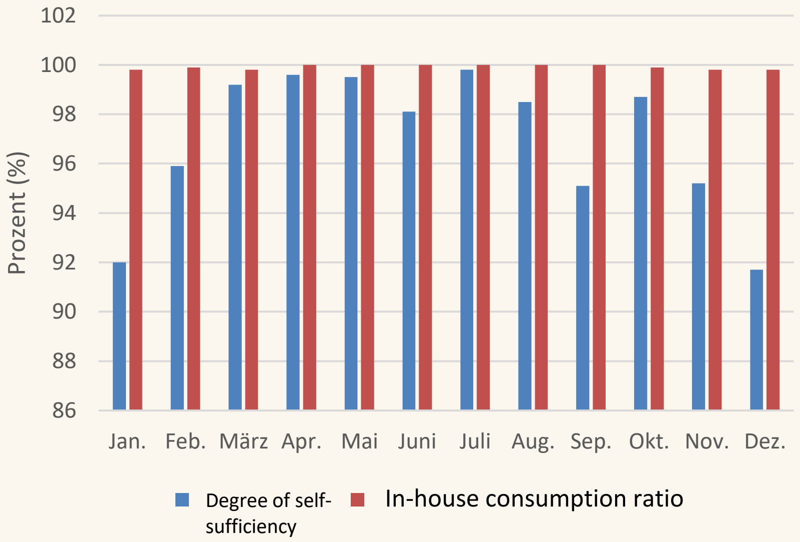


The result: The Frankfurt bridges have a high self-sufficiency rate and almost 100 percent self-consumption ratio

In summer, when photovoltaic electricity is produced or collected in abundance with the help of the Frankfurt bridges, the degree of self-sufficiency of the bridges is almost 100%. Only in winter do the bridges rely on drawing electricity from the grid - but at less than 10% of their demand. The self-consumption ratio is almost 100% throughout the year, as the bridges always either consume all the energy generated themselves or supply it to other users in the vicinity for direct consumption.

Self-sufficiency ratio: Ratio between self-supply and total consumption.
Self-consumption ratio: Ratio of self-consumption to self-power production.





Overview simulation results

Self-sufficient wheel and self-consumption ratio

Name	Unit	Year	Jan.	Feb.	March	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Degree of self-sufficiency	GWh	97,7	92	95,9	99,2	99,6	99,5	98,1	99,8	98,5	95,1	98,7	95,2	91,7
Energy consumption ratio	GWh	99,9	99,8	99,9	99,8	100	100	100	100	100	100	99,9	99,8	99,8

The high degree of self-sufficiency of the bridges can only be achieved by storing the large amounts of volatile energy: In batteries for the night or for short periods with little sunshine and in hydrogen for the winter.

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Electrical results of the simulation in the annual overview

Elektrische Resultate (Jahreswerte)

Name	Unit	Year	Jan	Feb	March	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Degree of self-sufficiency	%	97,7	92	95,9	99,2	99,6	99,5	98,1	99,8	98,5	95,1	98,7	95,2	91,7
In-house consumption ratio	%	99,9	99,8	99,9	99,8	100	100	100	100	100	100	99,9	99,8	99,8
Irradiation at module level	GWh	1.957	71	94	161	223	240	244	251	229	185	126	74	60
Pollution losses	GWh	9,0	0,3	0,4	0,8	1,0	1,1	1,1	1,1	1,0	0,8	0,6	0,3	0,3
Mismatching losses	GWh	17,5	0,7	0,9	1,5	2,0	2,1	2,2	2,2	2,0	1,6	1,1	0,7	0,5
Degradation losses	GWh	2,19	0,08	0,11	0,18	0,25	0,27	0,27	0,28	0,25	0,21	0,14	0,08	0,07
Cable losses	GWh	4,8	0,2	0,2	0,4	0,6	0,6	0,6	0,6	0,6	0,5	0,3	0,2	0,1
Ertrag Photovoltaik DC	GWh	414	15	20	35	48	51	51	52	48	39	27	16	13
Ertrag Photovoltaik AC	GWh	392	15	19	33	45	48	49	50	45	37	25	15	12
Own consumption	GWh	414	19	22	34	45	48	49	50	45	37	28	20	18
Direct consumption	GWh	339	15	16	25	38	41	42	43	38	30	22	15	13
Grid feed	GWh	0,31	0,04	0,03	0,06	0,01	0,01	0,01	0,01	0,01	0,02	0,04	0,04	0,04
Mains reference	GWh	9,3	1,6	0,9	0,2	0,2	0,2	0,9	0,1	0,6	1,8	0,3	0,9	1,5
Generated electr. energy Fuel cell (AC)	GWh	22	5	3	1	0	0	0	0	0	0	3	5	6
CO2 saving	Tons	47,8	17,8	23,5	40,1	54,9	58,1	59,3	60,8	55,1	44,8	30,8	18,2	14,9
Specific annual yield	kWh/kWp	949	35,3	46,6	79,6	109	115	118	121	109	89	61,2	36,1	29,5
Own power production	GWh	413,8	19,3	22	33,7	45	47,6	48,6	49,8	45,2	36,7	28,2	19,7	17,8
Total power consumption	GWh	400	19,5	21,2	31,2	43,2	45,6	47,5	47,9	43,6	36,7	26,5	19,2	17,9

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Thermal results of the simulation in the annual overview

Elektrische Resultate (Jahreswerte)														
Name	Unit	Year	Jan	Feb	March	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Degree of self-sufficiency	%	97,7	92	95,9	99,2	99,6	99,5	98,1	99,8	98,5	95,1	98,7	95,2	91,7
In-house consumption ratio	%	99,9	99,8	99,9	99,8	100	100	100	100	100	100	99,9	99,8	99,8
Irradiation at module level	GWh	1.957	71	94	161	223	240	244	251	229	185	126	74	60
Pollution losses	GWh	9,0	0,3	0,4	0,8	1,0	1,1	1,1	1,1	1,0	0,8	0,6	0,3	0,3
Mismatching losses	GWh	17,5	0,7	0,9	1,5	2,0	2,1	2,2	2,2	2,0	1,6	1,1	0,7	0,5
Degradation losses	GWh	2,19	0,08	0,11	0,18	0,25	0,27	0,27	0,28	0,25	0,21	0,14	0,08	0,07
Cable losses	GWh	4,8	0,2	0,2	0,4	0,6	0,6	0,6	0,6	0,6	0,5	0,3	0,2	0,1
Ertrag Photovoltaik DC	GWh	414	15	20	35	48	51	51	52	48	39	27	16	13
Ertrag Photovoltaik AC	GWh	392	15	19	33	45	48	49	50	45	37	25	15	12
Own consumption	GWh	414	19	22	34	45	48	49	50	45	37	28	20	18
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Grid feed	GWh	0,31	0,04	0,03	0,06	0,01	0,01	0,01	0,01	0,01	0,02	0,04	0,04	0,04
Mains reference	GWh	9,3	1,6	0,9	0,2	0,2	0,2	0,9	0,1	0,6	1,8	0,3	0,9	1,5
Generated electr. energy Fuel cell (AC)	GWh	22	5	3	1	0	0	0	0	0	0	3	5	6
CO2 saving	Tons	47,8	17,8	23,5	40,1	54,9	58,1	59,3	60,8	55,1	44,8	30,8	18,2	14,9
Specific annual yield	kWh/kWp	949	35,3	46,6	79,6	109	115	118	121	109	89	61,2	36,1	29,5
Own power production	GWh	413,8	19,3	22	33,7	45	47,6	48,6	49,8	45,2	36,7	28,2	19,7	17,8
Total power consumption	GWh	400	19,5	21,2	31,2	43,2	45,6	47,5	47,9	43,6	36,7	26,5	19,2	17,9

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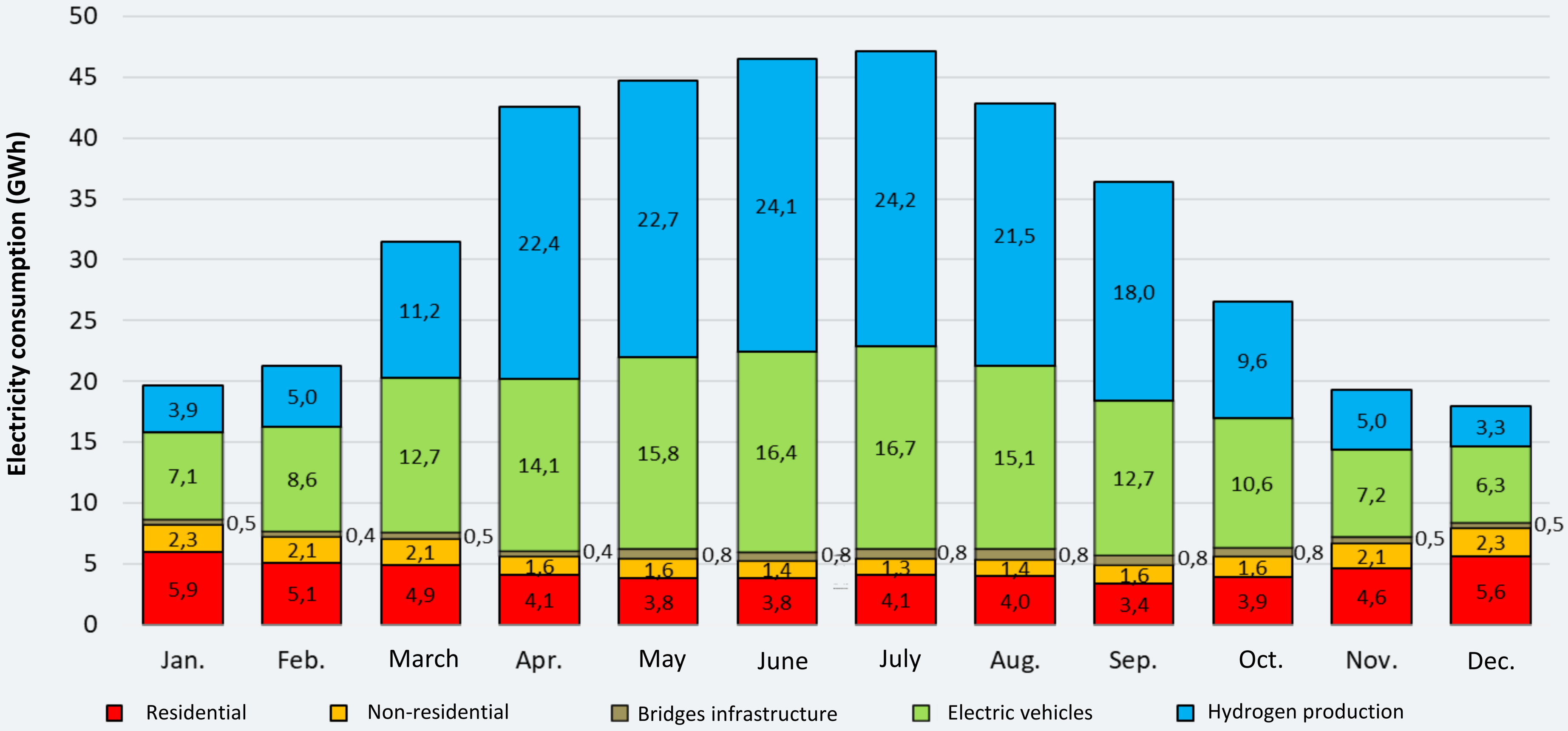
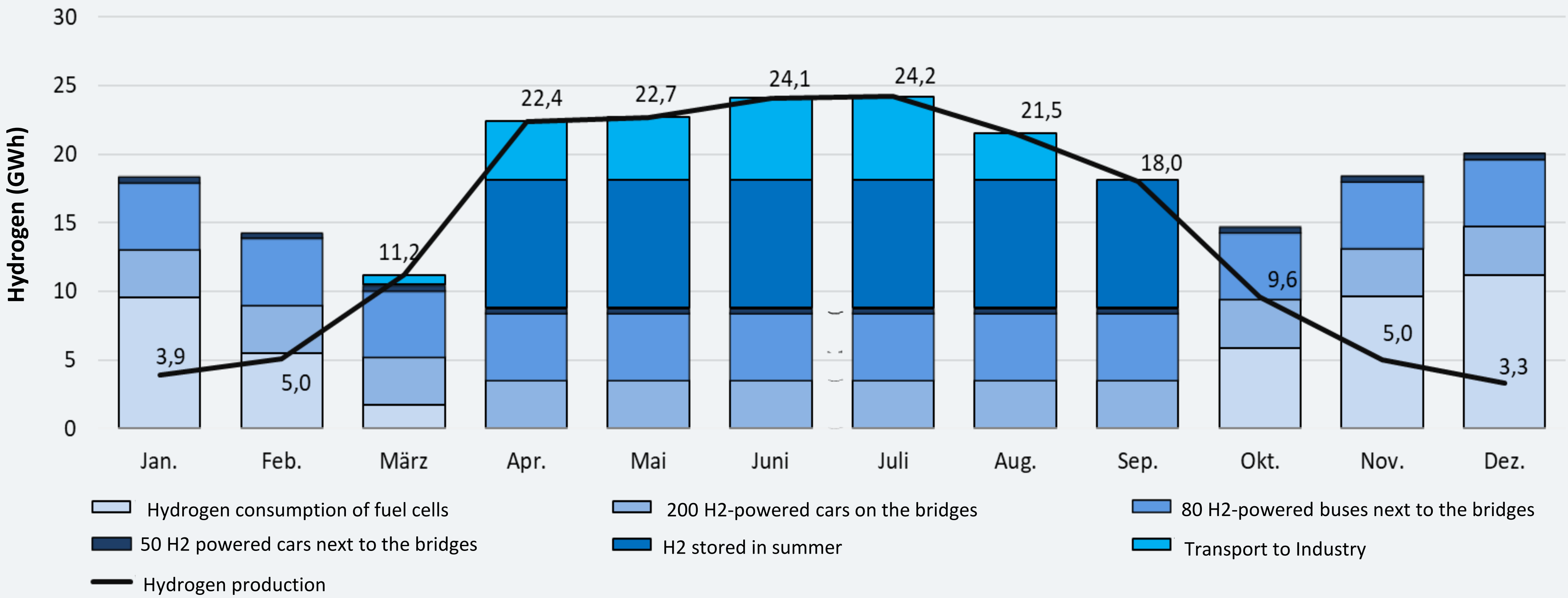
A large part of the energy generated by the bridges is stored in the form of hydrogen - formally, hydrogen production is attributed a corresponding "electricity consumption" here

In winter, too, surpluses from photovoltaic power generation are put into the production of hydrogen - of course to a much lesser extent than in summer



The hydrogen produced can be used for the vehicles on and next to the bridges and also ensure electricity production in winter

The largest share of the electricity generated (approx. 171 GWh/a) is used for hydrogen production: On the one hand, this can be used to supply H2-powered vehicles on and along the bridges all year round. In addition, the surplus of generated electricity in summer is "stored" in the form of hydrogen, so that in winter, when there is less sunshine, there is always an energy source that can provide compensation.



Free for further use - e.g. forwarding to hydrogen refueling stations

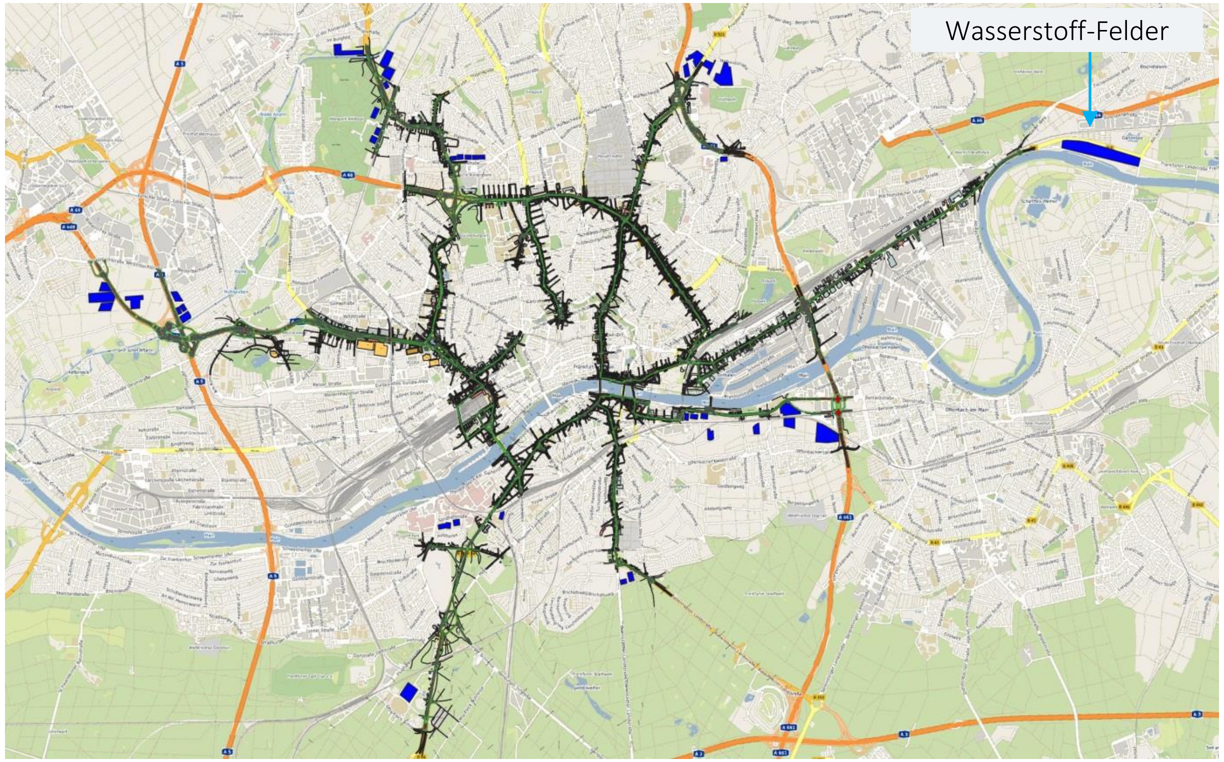
3,240 tons of hydrogen are produced p.a. with the 171 GWh of surplus electricity: A storage volume of 135,000 m3 is required to store these quantities at 350 bar in underground tanks

In order to produce the 3,240 tons of hydrogen in PEM electrolysers, 52,000 m3 of water are required. About 3% to 4% of the rainwater collected or stored in the cisterns under the bridges can be used as a water source.

Since the space required for 3,240 tons of hydrogen is comparatively large even at 350 bar, 42 farmlands and sports fields with a total area of 840,000 m2 were identified next to the 7 arms of the bridges that could be considered for hydrogen production as well as storage - however, only 20,000 m2 are needed. The use of these areas for the installation of the water tanks including the PEM electrolyser at a depth of 2 to 3 meters will not be affected - accordingly, it is attractive for the land owners to "lease" their subsoil for such an infrastructure, of which they hardly notice anything.

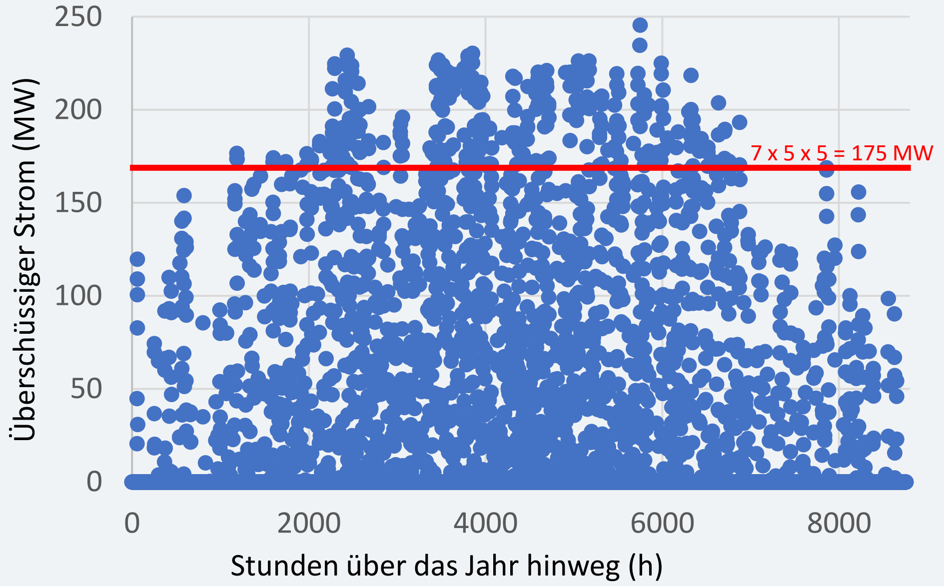
For each outer arm of the bridges, a "hydrogen station" is planned where hydrogen is produced and stored - in total, there are 7 hydrogen stations on the Frankfurt bridges.

The hydrogen is produced at the outer arms, but its consumption is distributed:
by hydrogen cars on or along the bridges
by fuel cells (for the purpose of electricity production in winter) in the supply centers.
There, it can be transported through the hydrogen pipeline system of the bridges.

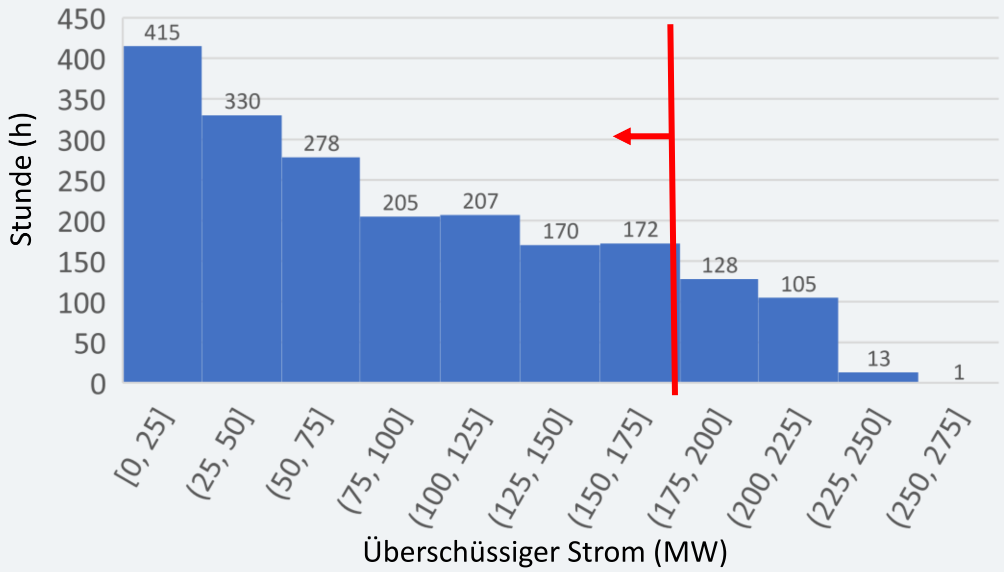


In order to be able to convert 90% of the surplus electricity into hydrogen in summer, 5 electrolyser stacks with 5 MW each are required per hydrogen station on the outer arms of the bridges

Surplus electricity for hydrogen production (MW)



Histogram of surplus electricity for hydrogen production (MW)



For the hourly observation of the electricity, the value on 1.1. at 00:00 hrs was taken as the 0 value.
For many hours in summer, the electrolysers operate at full power (175 MW) and produce 3.3 tons of hydrogen per hour. The upper limit is 175 MW, after which the excess electricity is fed into the grid.

415 hours of the annual operating hours (approximately 2,000 hours), less than 25 MW of electricity is available for hydrogen production. At the high end of the surplus, the number of hours per year is concise for 175 MW of excess electricity. To process this 175 MW (albeit temporarily), each hydrogen station requires 5 stacks of a 5 MW PEM electrolyzer.

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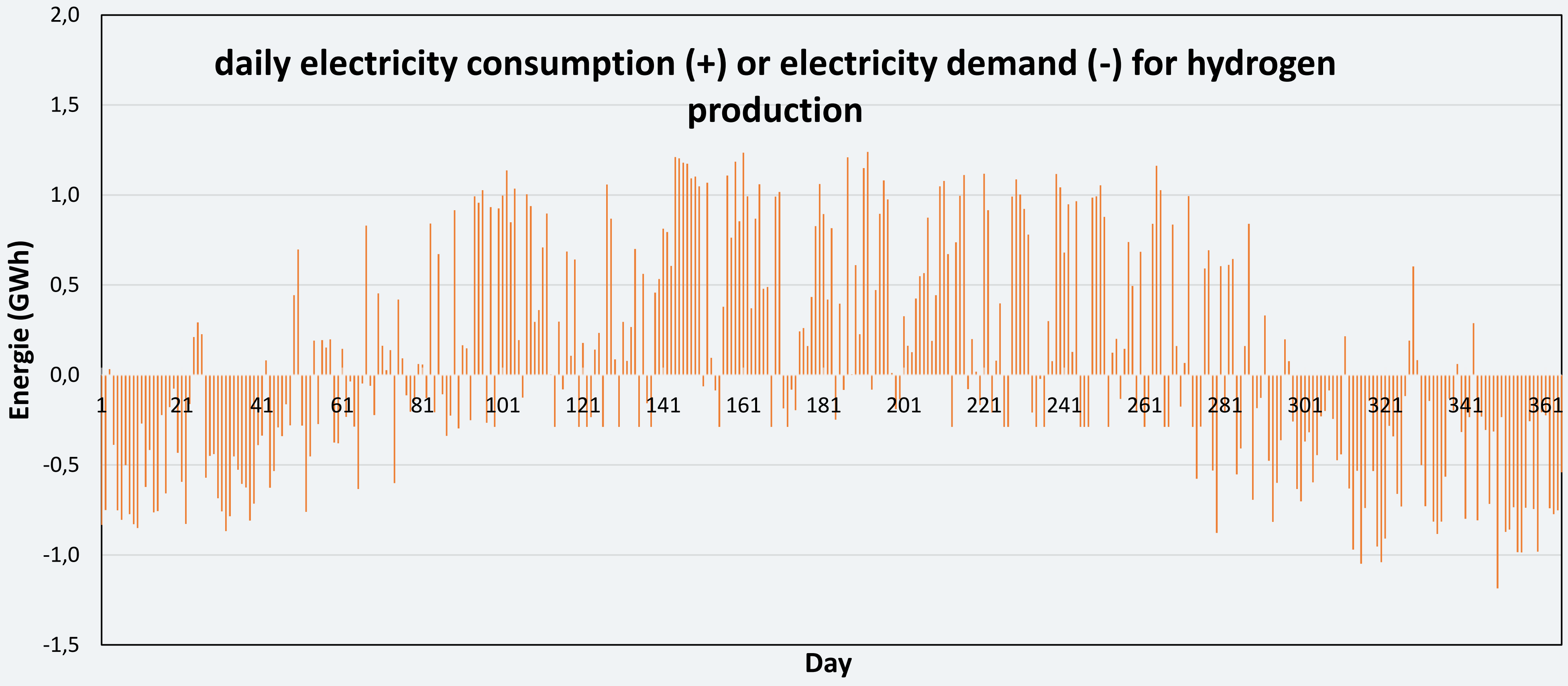
Of the 133 GWh/a of hydrogen generated in summer, 71 GWh/a (approx. 53%) are stored for winter

The produced hydrogen is not completely stored once to be consumed then, but there is permanently a more (in winter) or less (in the transition months) intensive consumption during the year: Therefore, only 41%, i.e. approx. 71 GWh/a or 1,345 tons in summer months, of the approx. 171 GWh/a surplus electricity used for hydrogen production is stored for consumption in winter.



Approx. 4,250 m2 are required for the hydrogen storage tanks, and approx. 450 to 500 m2 each for the PEM electrolysers - in total, this results in a space requirement of less than 5,000 m2 per station at the end of each bridge arm.

This "peak storage volume" has a space requirement of 56,000 m3 . Although a small part of the hydrogen can be stored directly on site at the bridges in the 200 supply centers located there: Each has a hydrogen tank with a volume of 3.5 m3 in one of its basements, so that of the total 56,000 m3, a total of about 4,900 m3 of hydrogen can be stored locally at 200 bridge points.

But most of the hydrogen, about 51,000 m3, is stored in the end sections of the 7 bridge arms in the 7 hydrogen stations -also underground-.

The tanks at the 200 supply centers are comparatively handy and compact at 1.5 m in diameter and 2 m in length, but the tanks at the seven hydrogen stations are much more complex to handle at 3.6 m D and 15 m L, especially since an average of 49 such tanks are needed for each of the seven stations.

Nevertheless, the space required for underground storage per hydrogen station remains manageable at around 4,250 m2 , especially since only a further 450 to 500 m2 are required for the electrolysers at each end of the bridge arm.

https://resources.plugpower.com/product-literature/ex-2125d-f041122

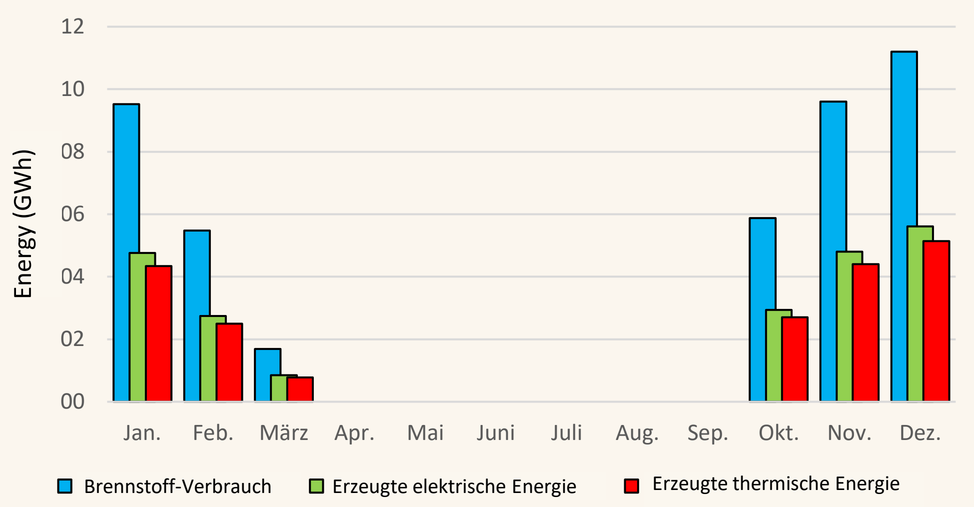
Input	
Stack Power Consumption	Up to 5MW
Voltage & Frequency	4.1 to 34.5kVAC 60HZ (USA) 11 to 33kVAC 50HZ (EU)
Water Consumption	13 liters per kg of H2 produced
Output (Hydrogen Gas)	
Volume	1,000 Nm³ / hour
Mass	2,125 kg / day
Purity	Up to 99.999%

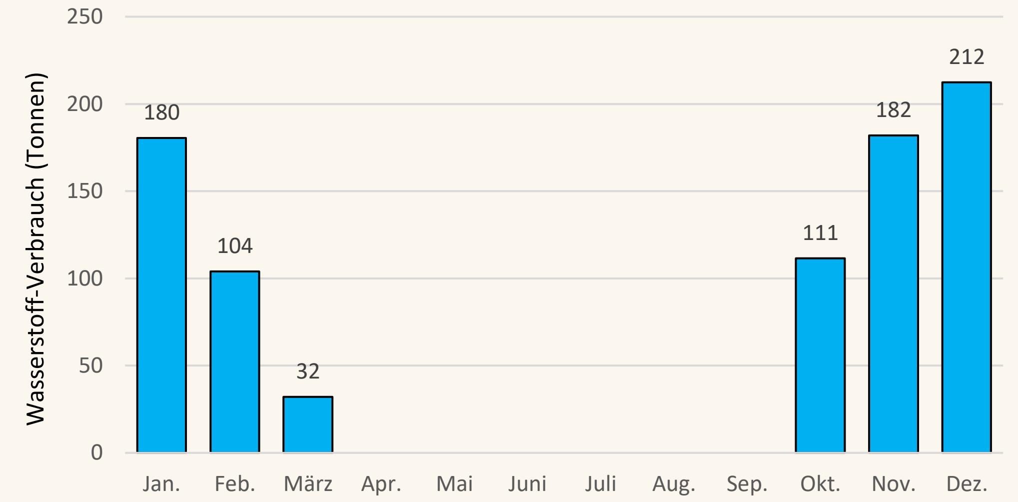
Pressure	40 barg / 580 psig (w/o compressor)
Operational	
Start Up Time	30 sec warm / < 5 min cold
Average Stack Efficiency	49.9 kWh / kg
Load Following	Instantaneous
Physical / Environment	
Installed Footprint	87.9 m² / 960 ft²
Ambient Temperature	-20°C to +40°C (wider temperature range

Of the 3,240 metric tons of hydrogen, around a quarter will be used to operate fuel cells, which can then also provide electrical and thermal energy in winter

Even in winter, when photovoltaically generated electricity as well as heat generated by solathermal means are significantly lower, the supply of electricity and heat must be ensured. This is done by using approx. 823 tons of hydrogen to operate fuel cells. These are primarily operated in winter to efficiently use the thermal energy generated at the same time.

Fuel cells with an output of 100,000 kW in total are required for the entire bridges: For this purpose, 200 fuel cells with an electrical output of 500 kW each are assumed, which are distributed to the 200 supply centers.



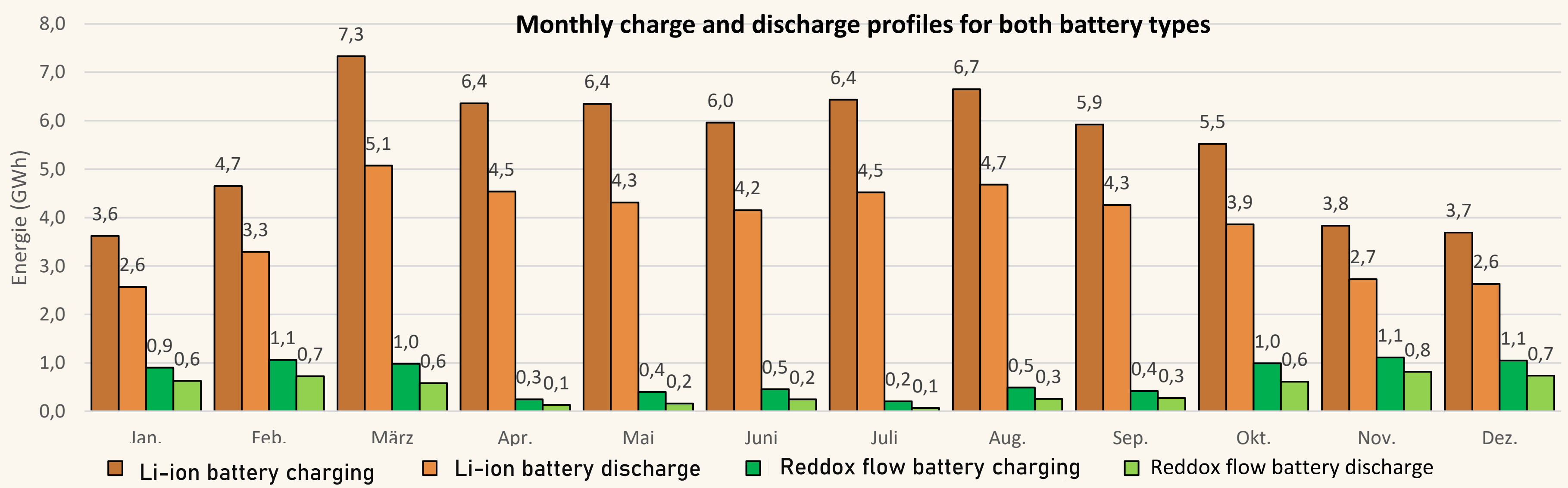


Fuel cells														
Name	Unit	Year	Jan.	Feb.	March	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Fuel consumption	GWh	43	10	5	2							6	10	11
Kraftstoffverbrauch	GWh	22	5	3	1							3	5	6
Generated thermal energy	GWh	20	4	3	1							3	4	5
Hydrogen consumption	Tons	823	180	104	32							111	182	212

While the hydrogen and the fuel cells provide a summer-winter balance of the volatile generated PV energy, the balance for shorter sunless phases and the night is provided by batteries

On the bridges, there is a total of 400 MWh of battery capacity in the supply centers. Of this, 320 MWh are Li-ion batteries and only 80 MWh are redox-flow batteries, as the latter take up more space relative to their energy efficiency. However, the battery concept of the Frankfurt bridges could be modified in the future when organic flow batteries are ready for the market.

The Li-ion battery capacity is distributed over 70 of the 200 supply centers (VZ). On average, Li-ion batteries with a total capacity of 4.6 MWh and a space requirement of approx. 33 m2 are to be assumed per VZ. The Reddox batteries can be found in all supply centers: In 60 VZ there are 2 each with 300 KWh and in the remaining 140 VZ there is one each with 300 KWh.



Battery charging and discharging														
Name	Unity	Year	Jan.	Feb.	March	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Li-ion battery charging	GWh	66,7	3,6	4,7	7,4	6,4	6,4	6,0	6,5	6,7	6,0	5,5	3,8	3,7
Li-ion battery discharge	GWh	46,9	2,6	3,3	5,1	4,6	4,3	4,2	4,5	4,7	4,3	3,9	2,7	2,6
Reddox flow battery charging	GWh	8,6	0,9	1,1	1,0	0,3	0,4	0,5	0,3	0,5	0,5	1,0	1,1	1,1
Reddox flow battery discharge	GWh	5,4	0,6	0,7	0,6	0,1	0,2	0,3	0,1	0,3	0,3	0,6	0,8	0,7

Organic flow battery

Li-ion batteries are more space efficient than redox flow batteries in relation to their energy efficiency: For the Frankfurt bridges, the 320 MWh Li-ion batteries require an area of (70x33)= 2,310 m2 in 70 supply centers (VZ).

The 260 80-MWh Reddox flow batteries occupy a total area of (260x3.6)= 963 m2 in the 200 VZs.

By the time the bridges are built, another form of battery could be added or serve as a lithium-free replacement: organic flow batteries, which are still in the testing phase.

Li-ion battery

https://www.tesvolt.com/de/produkte/e-serie/tps-e.html

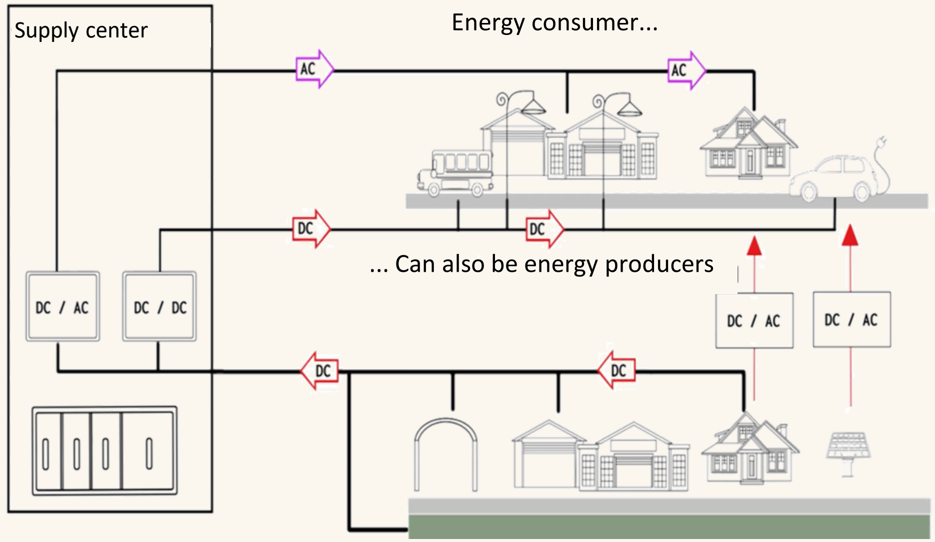
Reddox flow battery

https://lade-engel.de/LadeEngel-Batteriespeicher-bis-300-kWh-Battery-storage-pack-Stromspeicher-PV-Speicher/SW10023.8

Innovative energy supply infrastructure also takes into account the shortest possible transport routes between decentralized energy producers and consumers

With the bridges, Frankfurt is taking the first big step from centralized supply through power plant combustion to decentralized supply through renewable energies. Here, it is important that generators and consumers communicate with each other through a control system, a closed "Internet of Things," and that the energy is always consumed as close as possible to where it is generated: Distances of heat and power transport are thus shorter and conversion losses due to transformers or thermal losses due to line distances are minimized.

On the bridges, for example, all surfaces covered with PVT modules are energy-generating units. The electricity they produce is always first transmitted to the next supply center, where it is used in an optimally controlled manner.



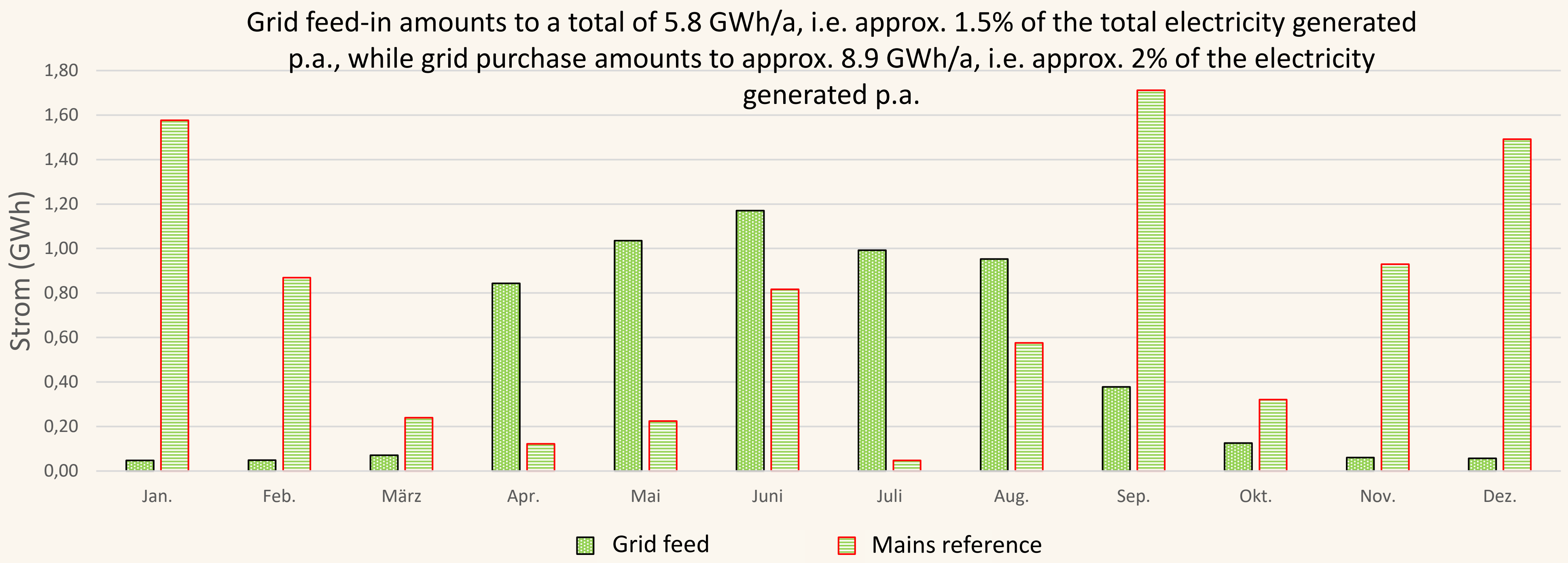
The photovoltaically generated energy is first used in the own supply section (in the vicinity of the nearest supply center). Once the demand is met there, the surplus energy is transferred to one of the neighboring supply sections that currently has more electricity demand than can be met.

And as soon as the optimal balance has been achieved on the bridges and there is no more demand, the surplus power is delivered to vehicles under the bridges or to PEM electrolysers for hydrogen production.

Another area of research to increase efficiency: avoidance of conversion losses. Theoretically, direct current energy generated by photovoltaics can be used directly to recharge e-vehicles without having to convert the direct current generated by photovoltaics into alternating current with losses. Only the voltage has to be adjusted.

Due to the storage landscape of the bridges, the demand on the Frankfurt grid from grid injection and withdrawal remains very low

In the case of the Frankfurt bridges, the exchange of electricity between the external and local grids is minimized: Surplus electricity is either stored in batteries or hydrogen is produced with it - both of which significantly reduce grid feed-in. Similarly, batteries as well as fuel cells reduce the amount of power drawn from the grid when there is a power deficit. Only in the months of September to February is the amount of electricity drawn from the grid slightly increased due to reduced solar radiation - but in total it is still comparatively low at 2% of the electricity collected or generated by the bridges.



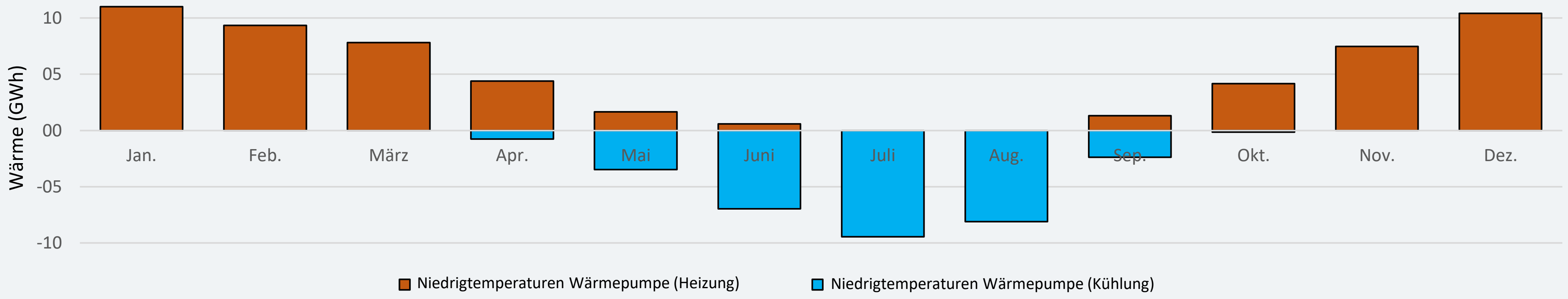
Mains supply and feeding														
Name	Unit	Year	Jan.	Feb.	March	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Grid feed	GWh	5,78	0,05	0,05	0,07	0,84	1,04	1,17	0,99	0,95	0,38	0,13	0,06	0,06
Mains reference	GWh	8,93	1,58	0,87	0,24	0,12	0,22	0,82	0,05	0,58	1,71	0,32	0,93	1,49

In the field of space heating and cooling, heat pumps are an important part of the bridge infrastructure

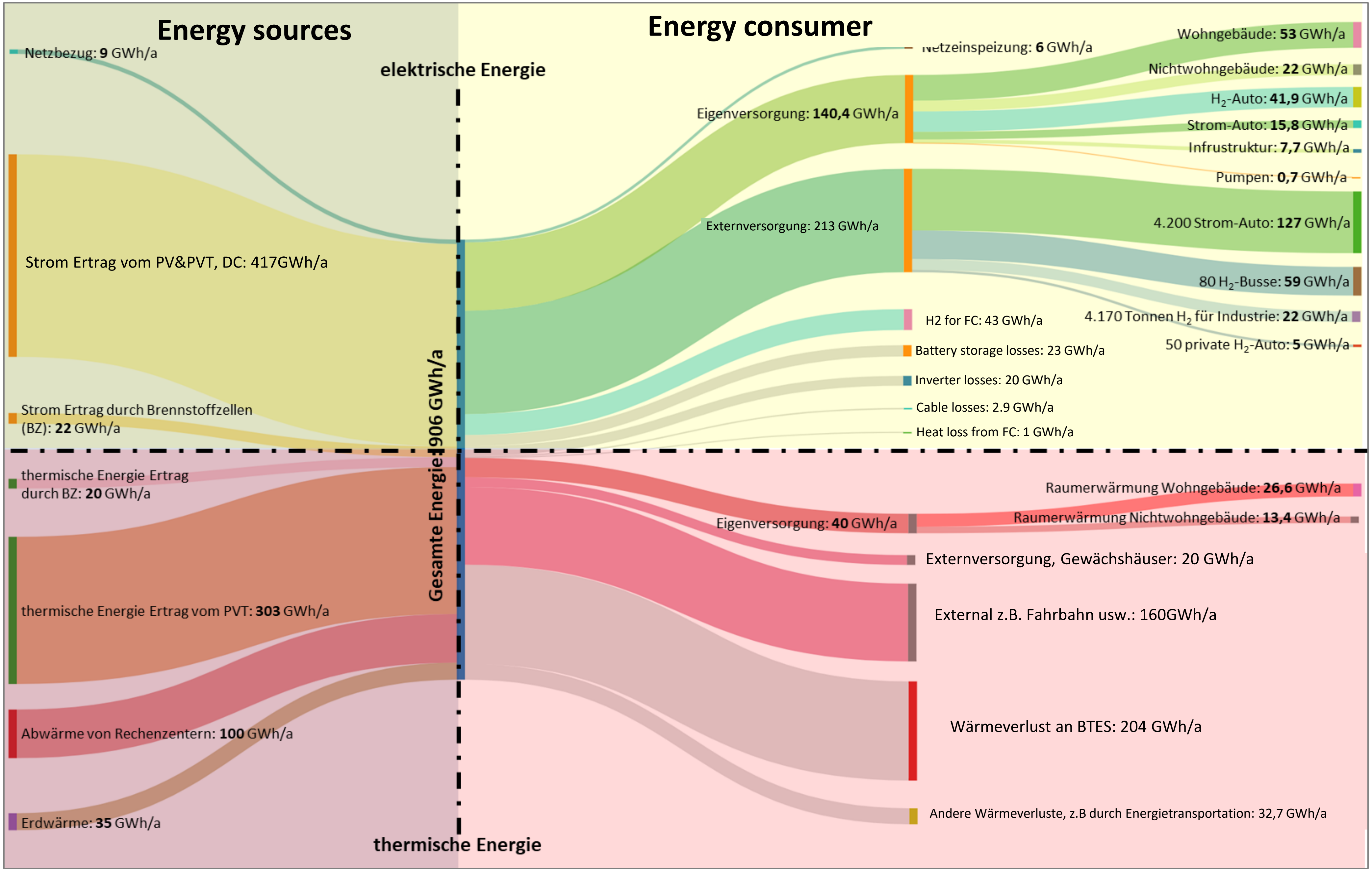
In the bridge quarters, heating and cooling is done with the help of heat pumps. They are installed in the supply centers when these supply several smaller buildings. Larger buildings on the bridges such as apartment buildings, retirement homes, kindergartens, etc. have their own heat pump. The system includes low-temperature (NT) and high-temperature (HT) heat pumps: the heat source for NT heat pumps is geothermal heat with a temperature of approximately 14 °C. Approximately 100% of the space heating and all space cooling is provided with the help of NT heat pumps. The buildings on the bridges and the greenhouses along the bridges require 100 NT heat pumps with about 290 kW heating capacity at W15/W35.

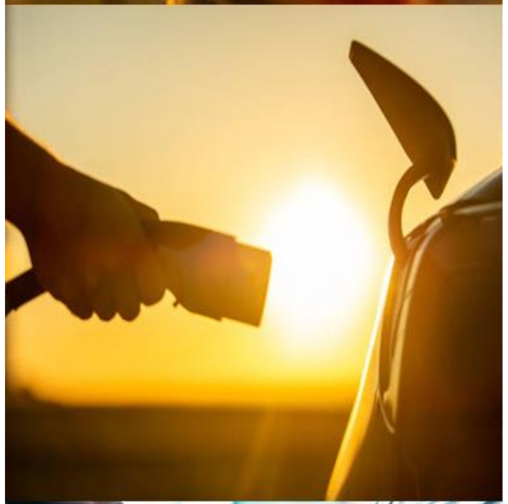
The heat sources for HT heat pumps are solar thermal from the PVT modules on and along the bridges and waste heat from data centers with a temperature above 20 °C.

In the first years, the HT heat pumps mainly provide heat for defrosting the roads on and under the bridges or swimming pools, etc., until the existing buildings along the bridges have switched from gas to heat pump heating systems in the course of renovations and the solar thermal heat and data center waste heat stored in the ground can also be used for these buildings. The COP of all heat pumps is between 4 and 7, depending on the water temperature.



Overview of all energy flows around the Frankfurt bridges





The bi-directional integration of the charging infrastructure of e-vehicles on and under the bridges expands the storage landscape and - scaled accordingly - can also provide control power optimized for demand

During the summer months, there is a surplus of electricity on the bridges, so it makes sense to use it to charge the vehicles parked along the bridges at the pillars. The pillars on the bridges will become charging stations wherever parking is possible.

A huge charging network is being created in Frankfurt, which can also distribute the excess electricity from the covered parking spaces to e-car users.

Conversely, all e-vehicles could also serve as energy storage units and return energy to the system when not in use, e.g., at night or in bad weather: the autonomously driving e-fleet on the bridges in particular, since it is fully controllable, but also the e-cars parked at the bridge pillars.

For this, a credit system can be developed that makes storing and releasing electricity attractive for vehicle owners.

With a corresponding roll-out, a corresponding reduction in capacity can result for the battery storage landscape of the Frankfurt bridges.

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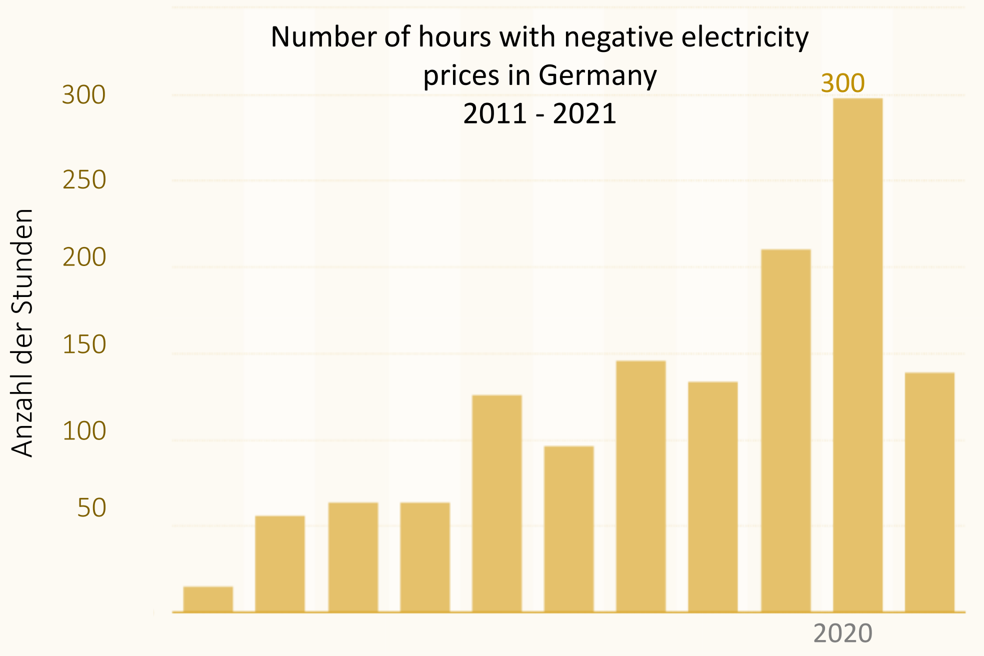
The greatest challenge in the future will not be the generation of energy, but its storage

The expansion of volatile renewable energies is also increasing the number of hours in which so much surplus is produced that the power grid would be damaged if the electricity were not got rid of somewhere. This is reflected in rising negative electricity prices.
Numerous studies predict for the distant future that there will be significantly abundant energy after the expansion of renewable energies.



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THE PLAN

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URBAN GREEN & NATURE
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Power requirement of the bridges
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Conclusion: With the Frankfurt bridges, the urban energy turnaround can be initiated in the midst of existing buildings

All components of electrical and thermal energy are controlled in their interaction in the infrastructure of the Frankfurt bridges in order to make optimal use of all surpluses of renewable energies and, at the same time, to avoid supply bottlenecks through state-of-the-art controlling methods.

Recording energy generation and consumption over time is the basis for designing a sophisticated storage landscape that will be the counterpart to volatile renewable energy in the smart city of the future.

The Frankfurt bridges can be the core of the smart city transformation of the rest of the city: They collect energy and transfer it to storage, they produce both thermal and electrical surpluses and release them to the city, and they serve as a platform to develop a modern grid control system including infrastructure that can then be transferred to the entire city.

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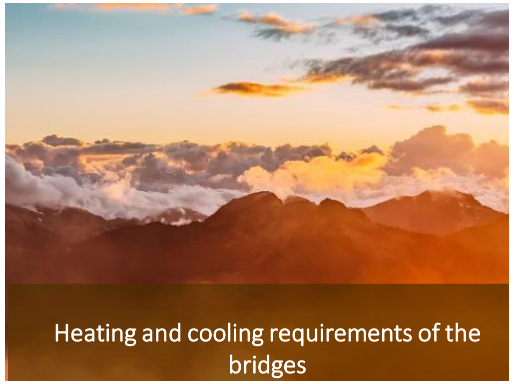
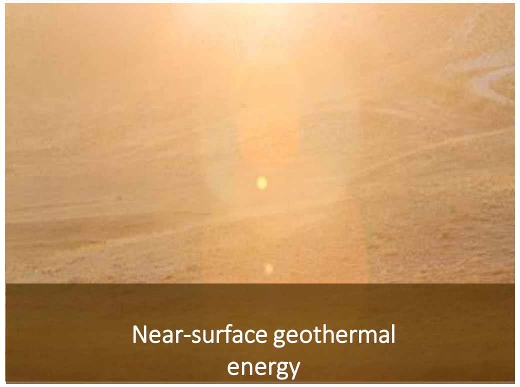
Electricity demand on the Frankfurt bridges


Photovoltaics as quarter power


Heating and cooling requirements of the bridges


Near-surface geothermal energy


The energy infrastructure of the future


The bridge world


Sustainability through technology


The Co2 balance of bridges

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Energy	Art & Culture	Technology & IT			Inspirers & Supporters