The Future of Ecological Urban Living

Matthias Ansorg, Samuel Buschhorn

Edgeryders OÜ

Contents

Contents

1 Introduction

What you will find here. This is a reference document collecting all kinds of unexplored ideas, little known and early stage solutions for ecological urban living in the near future. It is not your typical “green wellness” document recommending mindfulness and no plastic straws. Instead, this manual is intentionally extreme and radical, because that is the kind of response that we need in the current climate crisis and wider ecological crisis. This document is no ready-made instruction manual either, as the ideas are not yet ready for mainstream use. Instead, they are provided as inspiration for early adopters and urban living R&D labs. In our own organization, this is what The Reef aspires to be in the future; also, we are looking for other partners for this journey.

Structure. This document groups interventions into chapters by their primary goal or effect: for the climate, against waste, for biodiversity. Each sub-chapter treats a cluster of related interventions (“warm clothing”, “small heated spaces” etc.), where all these related ideas are treated in the form of a coherent text. Finally, tables and diagrams help to compare the relative impact and other properties of the interventions.

Acknowledgements. This manual has been created with the funding and support of EIT Climate-KIC, a European climate action organization. EIT Climate-KIC is supported by the European Institute of Technology (EIT), a body of the European Union.

Climate-KIC is supported by the
EIT, a body of the European Union

In addition, this manual as an open collaboration project received precious contributions from people in EIT Climate-KIC, the Edgeryders company and community, and from the Internet at large.

How to contribute. This manual is an open source project, and you are welcome to contribute yourself. However you obtained it, the most recent version is always a wiki on edgeryders.eu. After opening a (free) account on the edgeryders.eu platform, you can join the discussion thread below that wiki, adding your feedback, reports of problems with the document, or proposed additions. If you feel confident about your contribution, you can also directly contribute it by editing the wiki. The wiki uses Discourse flavoured Markdown for formatting, all of which is documented in our Discourse User Manual.

This is a wiki! Because this document is an open collaboration project with multiple editors, it is never really finished, just like Wikipedia for example. Expect to find some sections in draft state, to-do markers etc., because we keep working on and extending this document for our own purposes even after the end of the funded project where this document was started.

What is not included here. The following topics are outside the scope of this document and not treated here:

- **Well-known good practices.** There is little need for yet another document about well-established and well-known practices of ecological urban living. We only deal with the future here, with what goes beyond the status quo. This includes little-known good practices, innovations and also refutations, in cases where an established practice is not a good idea for ecological living.
- **Long-distance traveling.** Traveling within the city is considered part of urban living, but traveling beyond its limits is not. For long-distance traveling, we started the Green Travel Manual. And for measures to avoid business travel, see our Distributed Collaboration Manual.
- **Social and financial aspects. And motivation.** This document is about technology only – to derive value from it, you need to come with both motivation and money to apply that tech. It will not help you to create the right incentives for ecological behavior in a group, or to persuade investors to invest in your ecological living project. It will also not prevent you from housing a capitalist enterprise or other status quo protecting organization in your

ecological building. It will just tell you (right here and now): that would be completely self-defeating. Using ecological living techniques to hide the ecology-destroying nature of the status quo is called greenwashing.

- **Basic construction.** There is a lot to be said about alternative cement and more sustainable construction materials. But making o with the current building stock and maintaining it properly is even more sustainable, and already a full solution for construction during the current decades of severe climate crisis (hopefully ending 2050, and then we can focus on new construction as well).
- **Urban infrastructure.** There is a lot that can be done for emission reduction with changes to the city's infrastructure. This document is meant for building owners and inhabitants though, so it only covers what can be changed up to the scale of buildings. For innovations in urban infrastructure, we have another document called "An Autarky System for Cities".
- **Rural living.** For rural living, a very different set of green living techniques is possible. So we provide a companion document for that setting: "The Future of Ecological Rural Living".
- **Industrial production.** Urban households simply do not provide the space for industrial production, so we can't include this part. We do however include criteria to select the most eco-beneficial industrial products where it is necessary to rely on them. Also, maintaining and repairing any artifact used inside the household and small-scale production and product modification fall into our definition of urban living.
- **Industrial logistics.** This is a secondary problem following from centralized industrial production, and not a problem of urban living.

Estimation of household benefits. We try (and sometimes fail) to put numbers on everything proposed in this document, so you can choose solutions based on evidence and not simply comfort or instinct. It is the ecological equivalent of effective altruism: using data and evidence to find the most effective ways of not harming our natural environment.

The benefits of everything included here is numerically estimated relative to a "business as usual" scenario of a typical household (1) in the same climate zone (2) in a so-called "highly developed" region, because these are the households with the worst ecological impacts. Solutions are then ranked by the benefits for a household in the same climate zone – because this is a household manual, and households should be able to always choose the next suitable solutions from the top of the list. Note that solutions are partially overlapping, so the sum of benefits can be higher than 100%; for example, a transition to communal living may involve some of the same changes as a transition to smaller heated spaces or collective purchasing.

Global benefits. In addition, solutions are grouped together based on the estimated benefits when applied globally, into steps of reducing 50% of the remaining ecological impacts of human living activities.

2 Basic principles and techniques

2.1 Designing for mainstream adoption

To be relevant, there is no way around mainstream adoption of any future solutions for ecological urban living. The best way to design for mainstream adoption is to encapsulate complexity into either consumer products or commercial service offerings. In a way, in most European countries every consumer uses even nuclear power stations – mediated through the utility company. So basically every solution can be packaged or organized in a way that allows mainstream adoption. For most ideas discussed further below, this will be either a consumer product or a neighborhood-scale service offering.

2.2 Construction vs. usage

- **Consumption is 80% of the problem, construction 20%.** The energy costs of constructing a house is 20% of its total lifetime energy costs, while the energy cost during its lifetime of usage is 80%. When the building is well maintained and lives long, that ratio is skewed even more towards usage. This is why this document does not put much emphasis on construction but a lot on the activities of living, because that is where the greenhouse gas emissions etc. of urban living happen.
- **Innovation is hard. To make living greener, invest in human expertise instead.** Innovation of products and materials often does not work at the start, and requires a lot of experimentation before it is ready for general use.

  For a small-scale setup like a communal living space, a more appropriate way to innovate green living could be “process innovation” for building maintenance. Basically, build up a system so that the community can maintain its own space: train different members as plumbers, electricians etc. and also get the relevant tools so that all problems can be fixed with little effort, extending the building’s utility, lifetime, and eco-friendliness. Investing in human expertise cannot go wrong, while investing in new materials and technologies may go wrong.

  A simple example: a concrete wall made from some new composite is not self-maintainable and may thus only last 50 years. There is no real need for such a wall though, as brick walls have been around for hundreds of years and we know how to maintain them for that amount of time. Innovation is also important, but one of the greatest values of a building is that we can keep it alive, and that is an important aspect of buildings being “green”.

- **The impact of human care on buildings.** Buildings don’t last “100 years” like that, it can be 30 years or 300 years depending on the quality of their maintenance. So the cost of providing a function for a certain time is more determined by the care afterwards than by the initial investment. For example, Renzo Piano will rebuild the bridge that recently collapsed in Italy, with a version in steel that “will last 1000 years”, as he says. He did not mention with what maintenance. And bad maintenance was the main reason why the first bridge collapsed. So whatever you build, don’t care only for materials and high-tech, also care to put money into operation and maintenance. Because it is a new approach, this is innovative for the current time. Modern “sensor and IoT equipped” buildings can be a nightmare to maintain.

- **The cost of maintenance, and how to deal with them.** Nothing is re-used for what it because that is a lot of manual work. And manual work is not time efficient, and we have not enough money in Europe to pay people for much of their time anymore. Just enough to pay them for operating machines – everything else is manufactured by machines or in China. The same limitations apply to unique construction of houses – instead, all new houses now look very similar, and the look results from the optimization to be built with machines, not with manual work. Again, the same limitations apply to building maintenance: in earlier centuries, a building was always maintained so it could live “forever”. Now, buildings have an expiry date and are then destroyed and replaced, because maintenance is “too expensive” manual work that cannot be automated away.

  In communal living, there is no general solution to that, but at least a partial one. Namely, comparing the cost of worktime and machine work is just a financial comparison that does not capture all the value. By working less outside of the community and more inside, people will have fun making their own things “inefficiently”, and in total may prefer that to working for money and buying industrially made items. That’s even more applicable when starting to make things not from scratch but from the waste of the surrounding society, such as all the stuff one can take out of buildings before they are being destroyed.

- **Bring careful observation back to modern architecture!** The traditional architecture in different areas is very different, also within Europe. It developed over hundreds of years of incremental development. In the last 50 years, that changed a lot, so now most new houses all around Europe are built very similarly. Is that bad, and should we rather just trust the traditional, accumulated knowledge?

  Indeed, architecture always changes, and traditional knowledge gets lost. We don't understand a lot of building features of traditional architecture and material use. It's ok that processes change, the problem with the new processes is that they are not developed from careful observation of the objects and environment. For example, houses are optimized for efficient construction and not to last (because "cheap materials, expensive labor for construction and maintenance"). Similarly, commercial buildings like banks are remodeled every 7 years.

  New ways of ecological building can be informed from this process of "careful observation" of the past. That will allow to build with cheaper and more environmentally friendly materials in a way that achieves the same or better effects as with today's "modern" materials. In addition, careful observation can inform how maintenance can extend the lifetime of modern buildings to a multiple of their planned lifetime.

2.3 How to approach converting a building

- **Starting from an old office building.** The advantage here is that partition walls etc. can be easily removed and reconfigured.

- **Mobile conversion kit for temporary spaces.** That's a different approach to having an "own" space, and much simpler to realize: have a container with a kit to transform any abandoned building into a comfortable space within 7 days for 1-3 years of temporary use, with 2 days at the end to take all of that equipment out again. If this is about buildings that will be destroyed anyway, it will even be ok to remove walls and change the structure of the building when moving in. Utilizing abandoned buildings is also environmentally friendly because the continued maintenance extends the lifetime of these buildings.

2.4 How to approach architectural innovation

- **Exploring a proposal before it's built.** Architects to models a lot (actual physical models, not just 3D models). Others do a lot of discussions with potential users, to explore how they react to their design ideas.
- **Exploring construction innovations on a small scale.** For construction innovations aimed at large-scale application, architecture studios (like that of Renzo Piano) combine architecture with research. That however cannot really be pulled off for a single community building. There are also software packages for thermal modeling, light modeling etc. – these are useful for spatial innovation, not for material innovation. Because non-standard materials are hard to model with these software packages. It may be possible (with the PEB thermal modeling software package for example) but even for professionals, using that software is hard and expensive. Ideally there would be open source software packages that encapsulated the complexity and allows non-professionals to take over design and modeling tasks formerly reserved for professionals. However, that seems not to exist (yet).

  A more appropriate technique for such a setup is to create a setting (both physical and by social organization) that is welcoming the construction innovations. This can include, for example: a building that is simple to re-configure; piping and wiring that allow to install new innovative machines and devices wherever people want; a large on-site workshop that allows to adapt the building and its equipment quickly.
- **On new facade materials (like PV panels).** There is a house in Australia using PV panels as roof covering, somewhat tilted so that light can still get through to the inside. In architecture, there are multiple uses of wall finishing / cladding: weather protection, and allowing the building to breathe (humidity transfer to the outside to prevent humidity buildup, mould, dampness indoors etc.). Depending on weather condition, the outer layer is of different permeability, impacting how the building is breathing. In some parts of Portugal, tiles are used for example.

  So to start hacking together a new cladding system (such as from PV panels), a good tip is to start with experimentation. Nothing too big, nothing too drastic at the start. "Play with it." Just to see how the material behaves, how it can be attached etc.. It will be difficult to pull off such a hack, as the material was not designed for such a use, so may perform worse for it than industrial cladding systems. Or at least it will probably not perform better. For PV panels, a purely ornamental use (plus power generation of course) of PV panels, or a use as a sight protection / separation wall on a fence or similar, could be the first experiments, as not so much can go wrong.

2.5 Dealing with legacy laws and regulations

Routing around regulations. If you have no close neighbors, it is much simpler to ignore regulation because there is nobody who will complain to the authorities. Also, try to break only rules for the inside, not in relation to the outside environment. Then, the problem only arises when you want to sell the building – then an architect will have to check what has to be changed for that to be possible. So that will be the time to undo ones hacks and changes – and when keeping the house, it will never be a problem.

Combining houses in the city. Buying adjacent houses and making them into a single house by knocking down walls is prohibited in Brussels. But you could just do it, and put up the walls again when moving out :slight_smile:

Dealing with fire safety. In cities, public and communal spaces are tightly supervised by the fire brigade. They may mandate the type and material of walls, fire protection doors etc. to isolate buildings against each other so that there is a safety window for people in one part if another part catches on fire. For example, staircases in large buildings will have to be isolated from a kitchen space with a fire safety door.

Certification issues with material re-use. Any certified component of a building is not legal to be put to use again in a new building. The certification only applied when that equipment was installed the first time, but now the standards might be different and not cover these items anymore for getting a new building certified. For example, emergency lamps. All these items are now considered waste. It especially also applied to electronics components.

2.6 Take it to the neighborhood

By integrating social projects such as clothing exchange events and rescued food distribution, a communal household or other group can make the living in the whole local area more green, not just its own. It would be interesting to do the numbers for that, and it may turn out to be the most efficient way of emission reduction. From @Bernardo's experience, a best practice to do these social service projects is to do those that also profit yourself, because then it's not a net drain on the organizer: if you have kids, organize kids clothes exchange events; if you cycle, organize a cycle repair workshop; if you like dancing or working out, offer dance classes or open a gym in the communal space.

These can also be semi-commercial activities and still be a net benefit for the neighborhood. It provides a public good because of "zero marginal cost": scaling the service up to more people beyond ones own and direct community's needs does not really cost more, so can be provided as a service at a low price or even for free.

2.7 Household consumption accounting

The lifetime of a well-maintained building can be considered to approach infinity – the building is never used up in its entirety. Then, all ecological impacts of a household happen connected to the material and energy flows into and out of the house. Tracking these flows is quite a realistic task using energy meters, water meters, scales and barcode scanners. With barcode scanners, it is simple to record what purchased packaged items enter the house. With that setup in place, household level GHG accounting and optimization is also realistic.

Note that, to keep the accounting low-overhead, the unit of accounting is the household not the person. Nothing done in other households (living in a hotel, eating out etc.) is taken into account, as that is thought to belong to the accounting of other households. The disadvantage is of course that households are very different so that comparing results with other households is not simple – however, a rough estimate of (more comparable) per-capita greenhouse gas emissions can be made by adjusting for person days in the household and including long-distance traveling. And the main purpose is anyway to make progress over time in this one household, not to compare with others.

2.8 It's all about resource efficiency

In spite of all ecological zeal, we'll never propose that any human being has to leave Earth earlier than it will happen naturally to them. We'll also not question the ultimate (non-material) life goals of anyone, whether they want an interesting, happy, beautiful or meaningful life. With these constraints, there are only two things we can do to save our ecosystems. First: not making so many new people. Second: finding the most resource efficient way to have the life you are looking for.

So if you are looking for happiness in life, it is not enough to achieve this, but to achieve it with as little resource consumption as you possibly can. In other words, frugality is the supreme value for this time of ecological crisis. In current Western societies however, people do not have this value; frugality is demanded from technology only, not from people. And even where government demands frugality from technology by setting resource efficiency standards, it is all too easy for companies to circumvent this by planned obsolescence, pseudo-innovations etc.. Governments are also not serious about frugality, because if it would indeed lower the absolute amount of resource consumption, then it would be hard to impossible to still grow the economy – trading resources to consumers for “consumption” is the major way how GDP is made, after all.

2.9 Taking back tasks to the private space

Modern Western society since the 1950s is a history of the socializing of tasks that were earlier taken on by the extended family, such as childcare, care for the sick, care for the elderly and so on. And the public system for doing these is very inefficient: not only does it require to build, maintain and heat houses in addition to the existing homes of individuals, the public system is also overly cautious to avoid claims of damage compensation and similar issues and thus needs many more resources for the same task.

2.10 The Internet enables efficiency like nothing before

Right now, much of the Internet is a commercially dominated space for advertising. But technologically, it is the most efficiency-enhancing technology that humanity has ever had: it can provide a fully automated, society-wide and truly global resource coordination system. The notion of “fully automated luxury communism” is not far. Very little of that potential has been used so far.

3 Lifestyle and living

3.1 Ecologically responsible childcare

Communal childcare is ecological. When homes have safe spaces for children, community members can start to care for groups of children. That relieves other community members to do other work and also is much more efficient than the public kindergarden system, both in terms of costs and ecologically, because the kindergarden building does not have to be built, heated and maintained, and also no transport of children to and from that building is necessary.

Spaces for efficient supervision of small children. Childcare should be integrated with the normal living area as much as possible to require as little as possible direct adult supervision – because that is efficient. For small children for example, a good choice is to provide the building with a large inner courtyard with child-safe toys, plants etc..

Unsupervised child play. In a communal space that is somehow enclosed (not like a gated community, but a bit …), unsupervised play is simple, even in today's age and in cities. Children can become quite self-sufficient – @alberto mentioned how in such a neighborhood in Milano, the children made all the adults keep their doors unlocked so the kids could go in and out of the houses of their friends to get water, go to the toilet, meet their friends etc.. It made the environment more social for everyone, and is more efficient regarding adult attention. It's not directly "green", but frees up precious time for other activities, including for those that take more time but less other resources and are thus part of "green living". It also lowers the need to move children around in a car between activities.

Provision for children activities at home. "Do you really need your children be driven to karate and back? Make them a football place in the courtyard instead." And similar approaches. It uses less energy for transport, and it frees up adult time for other aspects of a greener lifestyle, which is often more time-consuming.

3.2 GHG offsetting

It may turn out that emission offsetting by donating to the various schemes created for this purpose is, for the time being, the most effective intervention for the climate that affluent urban residents can make. This will change once the low-hanging fruits of carbon offsetting are gone and demand for it rises, at which point the price (EUR / t CO2e) will rise and some local solutions to avoid emissions become more cost effective. But for the time being, earning more money and donating it for emission reduction could be best for everyone who *can* earn more money.

3.3 Work / home integration

Offices are a very inefficient use of space: they are empty 16 or 24 hours a day, and still consume resources and represent embodied energy and emissions. In addition, workers have to travel there and back to their homes. Rather have your office in your home, for example a super-easy-to-clean room that is an office during the day and a party room in the evening. To be easy to clean, dangling furniture mounted to the ceiling could be a new approach.

See the Distributed Collaboration Manual for detailed tips on how to work with your colleagues when you work remotely from your home.

3.4 Avoiding material consumption

A household's energy consumption can be switched to be green fast and easily: just switch to a provider of renewable electricity, ditch the car, and use heat pumps for space heating. This is very different for all material consumption, as the industrial processes happened in the past, far away and in a complex network of suppliers, making it impossible to guarantee that any physical product was produced "sustainably".

For this reason, material consumption should be avoided as radically as possible. Another reason is resource depletion, because in any not-fully-circular economy, material consumption permanently increases resource entropy, making resources permanently unavailable for future generations.

The ways to avoid material consumption are nicely summed up in the 4R principle ("Reduce, Reuse, Recycle and Recover"), however it needs some unpacking. For example, it entails the following changes, some obvious and some not:

- **Plastic-free shopping.** Have a (communally researched) list of local purchase options etc. for no-plastic-packaging food etc.. Share your grocery shopping –

that is needed to be able to get items plastic free, as plastic-free shops might be further away, or sell in larger quantities.

- **Fashion is a psychological issue.** Fashionable and new / clean looks is not a criterion to decide if a resource (clothing, car, furniture) is still good to use or should be discarded.
- **Sharing.** Sharing resources is a way to reduce their number, such as tool sharing in a neighborhood tool library.
- **Caring for stuff.** Good operation, protection and maintenance is a way to reduce the need for material products, because they will break less often and will be sufficient even when not performing like a newest-generation product.
- **Protecting mobile electronics.** Mobile tech life extenders: many notebooks and mobile phones break because they are mishandled or accidentally dropped. With proper protection and efficient aftermarket software like Linus for notebooks and LineageOS for mobile phones, they can live for more than 10 years. Many waterproof and shock-protecting cases are available, and it makes a lot of sense to get one of the toughest ones possible, esp. for people with a history of dropping or losing things.
- **Buying used.** Buying used items reduces the demand for new items.
- **Paper-free living.** There is very little to no use for paper in modern society, but it will need a deliberate effort to stop junk mail deliveries, magazines, bank statements and cardboard boxes from coming to the house. Cardboard boxes from online shopping are probably 80% of the problem. Technically, stackable or foldable plastic boxes (with cardboard layers on the outside due to the regulations of parcel delivery operators) are a feasible solution, but so far only when shipping parcels among friends and relatives as individuals won't be able to persuade online shops to use them.
- **Electronic alternatives.** Sometimes, you can replace material consumption with energy consumption. For example, downloading a film instead of buying a DVD. Or downloading an e-book instead of purchasing, transporting and storing a book.

3.5 Compostable trash

Not all material consumption can be avoided – for example, some food items will always need a way to package them, and if that food is not produced in the local area than the packaging will probably be single-use. Similarly, parcels will arrive as cardboard boxes for quite some time.

However, trash that is compostable is not much of a problem because it becomes soil again, a valuable resource, esp. in organic agriculture. Composting is in fact carbon-negative because it sequesters carbon into the soil, while biomass burning is at best carbon neutral. (Biomass charring with partial combustion is another matter though, as that can also be carbon negative through biochar as a soil amendment.) Transporting the soil that cannot be used in the backyard garden to agricultural land is still a problem, but not as much as the organic trash it is made from because it lost mass and volume by composting.

This is an argument for a proper in-house composting facility, ideally combined with heat recovery (see section “Heating with compost”). And then, for maximizing the proportion of matter that enters the house and can be composted. This includes paper, cardboard, kitchen scraps, wood scraps from furniture, organic packaging material like leaves, papercrete etc.. Even human feces, see section “composting toilet”. The long-term goal would be that >99% of all material entering the house is compostable, even including the insulation material of the house, wall building material like papercrete etc.. When applied to a whole city, this solves at least 60% of the whole “reverse logistics” for trash collection and management.

3.6 Neighborhood services

Neighborhood services are a potential multiplier of ecological living practices. A communal living space has enough people to staff these kinds of offerings, and when selected well they can make both practical and economic sense for the communal house, even provide a business. Some example ideas are collected below:

- **Distributing rescued food.** This can for example be done as parts of regular events where the whole neighborhood is invited and where food is available on a donation basis. A communal household is still a private space, so many of the legal rules applicable to commercial handling of food will not apply here, which makes this a low-overhead, pragmatic way of rescuing food. For details, see section “Against food waste”.

- **Things lending service.** To reduce the number of tools and other things a household needs to own, a neighborhood-scale or even city-wide "things logistics" service is a great, unexplored opportunity. It can be provided by a communal household that has a lot of storage space available, and at least one delivery person and one storage worker.

  Technically, there would be an open source application for searching tools and parts in the storage and ordering them within a certain time window, either for delivery or for pickup. See our analysis of suitable open source software. In addition to lending, other things (esp. parts from product disassembly) would be available for purchase via a regular webshop software.

  Delivery would ideally be possible 24 hours a day, just more expensive at odd hours. A software would dynamically organize the driver's travel route based on the pickup and delivery jobs. For delivery, a cargo e-bicycle would be employed, as that is both fast and ecologically responsible. Since most items will not be packaged for transportation (they are all used anyway!), a cargo bicycle can transport a lot of items in a small volume, probably 300% as space efficient as the storage space of a parcel service van, and even more when also considering the dead space consumed by the van itself.

  Items that can be included in such a lending system are for example:

  - general household items, kitchen utensils and workshop tools
  - household items for parties
  - spare furniture for parties and hosting, optimized for transport by the cargo bicycle
  - special-purpose furniture such as outdoor tables and chairs
  - rescued food (see above)
  - salvaged items (see below under “salvage service”)

- **Salvage service.** One of the worst cases of resource wastage is trashing items that are still good to use because they are no longer needed, would consume scarce storage space and there seems to be no economically worthwhile or at least time-efficient way to transfer them to somebody who has a use for these items. As the cost of physical consumer products has been decreasing a lot for several decades now, this is a growing problem. It is of course connected to values of consumers, but these are hard and slow to change. Instead, what will also solve this issue is providing a fast and comfortable opportunity to get rid of such items, ideally even receiving some form of compensation. This is what a neighborhood-scale or city-scale “salvage service” would provide: getting rid of an item is as simple as dropping it before the front door and taking a photo of it with the salvage service’s app. That orders a pickup by somebody with a cargo e-bicycle. After transport, the item’s value will be estimated and that will be credited to the original owner’s account. With that balance, people can then use other services such as the “things lending service” (see above). Because transport within a neighborhood is fast and efficient, in principle any item that has a remaining use value can be salvaged via this service, including but not limited to:

- any re-usable items that somebody wants to get rid of, from flower pots to clothing
- re-purposable items, from cardboard boxes to beverage cartons and polystyrene foam
- broken tech items, for repair or disassembly into re-usable parts
- recyclable items, for example organic trash for composting

- **Local business database.** Should include all shops / businesses in the city and the surrounding villages, and also all the products they have, as long as they are interesting for potential purchasing. Businesses further away would also be included if they sell something that is rare / precious enough to be purchased from further afield.

  By providing others access to this information online, it basically creates a local online shopping platform.

  The commune would of course prefer to buy local products in order to create and support the local economy. And that is how it would use this business database: instead of purchasing something from a big city or from abroad, commune members would first evaluate if they can get alternative products from the local area. This will be true for many agricultural items, spices, herbs etc., and also for furniture, basketry work, blacksmith work etc..

- **Map with points of interest.** This should esp. be integrated with the local business database, but will also have other POIs besides that. See: "Creating a 'Points of Interest' map with open source tools".

3.7 Workshop, parts and a handyperson

A building with 15 or more inhabitants that intends to emphasize ecological living can afford to employ one handyperson for building management, usage optimization, repairs and custom manufacturing.

That person will come with a complementary skillset of broad handicrafts and tech knowledge, a workshop and parts store that together enable a multitude of ecological living techniques that are not possible in smaller households:

- When there is a person who is paid to monitor and optimize a building's energy and resource efficiency, the incentives stack up correctly for this task to be done. That alone might already pay that person's full-time salary. In normal households it's the opposite: inhabitants are careless with resources because that allows them to have more time or energy to earn the money to pay for that carelessness "and some more".
- Inhabitants can drop off household appliances and electronic devices to be repaired, or even better do the repairs together with the handyperson. As there will be a store for all kinds of parts and tools to adapt parts and even manufacture custom parts, repair and maintenance jobs become much cheaper. For example, with 10 broken bicycles you can keep your own bicycle running for free, forever.
- Furniture can be repaired and even custom built from parts of old furniture, trashed furniture, homegrown bamboo etc. and other material found in an extensive "parts library" near the workshop. There is no need to ever buy new furniture.
- Inhabitants can design small helpful devices together with the handyperson, and manufacture them with in-house tools incl. a 3D printer. These devices will be very specific for the local context and can enable idiosyncratic energy savings and resource efficiencies that are impossible with purchased products.
- Inhabitants have a patient mentor to learn new tech skills themselves incl. bicycle maintenance, computer repairs an other useful skills for their personal

future. This can be extended into neighborhood-scale handicrafts events and courses, which over time will enable a lot of people to provide items from home-based repair, remanufacturing and production, rather than from purchasing anything new.

- Inhabitants are welcome to drop off any unused item in the parts library and tell what should be done with it (lending, gift etc.). The handyperson will catalogue and sort it in accordingly, and somebody else from the household or neighborhood will use it again at the next opportunity. This makes reuse so comfortable that people will actually do it, esp. since it provides the immediate benefit of physically getting rid of “useless stuff” that will then reside in the parts library.
- The handyperson will collect certain types of wastes from the neighborhood and city and can do hacks and remanufacturing with them that are impossible in industry because they cannot be automated or because of safety concerns for consumer products. Examples include: harvesting solar cells from broken photovoltaics modules and building new modules from them; harvesting lithium-ion cells from broken accumulators and creating “free” battery storage for the house from these.

If the household cannot afford paying a normal wage for this as a job, then the job could also be the equivalent of a live-in nanny job for a handicraftsperson: instead of caring for people, that person cares for things, in exchange for a place to stay, food, health insurance and a moderate amount of money. That person might come from abroad, just as live-in nannies often do.

3.8 Automated building control

It seems that a lot (!) of energy efficiency and resource efficiency can be gained when controlling indoor temperature, humidity and electricity consumption with an integrated electronic system, running open source software that can be easily adjusted by the building inhabitants and that is intelligent enough to optimize internally for how to achieve its goals. Example functions would include:

- Deciding when it is better to purge excess humidity by heating and ventilation in intervals, and when it is better to use chemical absorbent that can be regenerated with heat in the summer again.

There is also value in having a peer-to-peer relationship between this technological system and the inhabitants, collaborating to achieve high targets of resource efficiency. This is different from the usual scenario where humans treat “their” technology as a slave. For example:

- The house control system might realize that it would have to start burning heating fuel soon as the heat buffers run low, and in turn might ask humans to use prepared room separation measures to close off some spaces as unheated space during the passing of a cold front.
- The house control system might realize that room temperature in a certain room is abnormally high, and send a human to investigate.

4 Food

4.1 Saving energy in the kitchen

Today, the kitchen is the only remaining locus of production in an urban household. That's why, apart from building heating and hot water generation, this is the place where most resource efficiency is lost and where most can be gained again. Below is a collection of various energy-saving ideas for the near future.

A more efficient water kettle. Current electric water kettles have a minimum setting for the amount of boiling water that they can produce; since often only one cup is needed, avoiding that minimum setting and providing a clear indicator of water amount to boil can reduce the energy needs by about 40%. Some more energy can be saved by insulating the water kettle. And then some more by a target temperature setting – some tea water is supposed to be about 80 °C for example, and heating it just to let it sit to cool a bit is a waste of energy. Also, current electric water kettles currently use resistive electric heating. That is close to 100% efficient and sustainable as long as the electricity is sustainably sourced. However the grid is far from 100% sustainable electricity, which means that everything that lowers electricity consumption helps to bring it there. So instead of resistive heating, the water kettle could use heat pumps, which are up to 350% efficient currently. One design might use a heat pump to heat up to 80 °C (which is within range of current heat pump hot water generation) and then then resistive heating to heat it the last 20 °C to boiling. An alternative design might be to just connect the water kettle to the hot water piping with very short piping to the house's central heat pump water heater, and then to use resistive heating again for the remaining 20 °C.

Other interventions. A list of ideas:

- putting lids on pots (predicted to save 120 kWh/a per household, see no. 22 in that document)
- pressure cookers and humidity
- insulated pots and lids: the insulation would be vacuum insulated stainless steel vessels, as known from cans and cups for hot beverages. For electric cookstoves, the pot walls and the lid would be insulated. For gas cookstoves, the outside of the pot skirt and the lid would be insulated.

- energy savings of communal cooking vs. cooking for 1-2 people
- energy saving recipes, incl. cold meals
- slow cooker as a kitchen appliance
- cooking with biogas and hydrogen

4.2 Ecological diet

Here are measures for an ecologically sustainable diet – both the well-known obvious steps and a innovative ideas that will have to be researched more:

- **Low-carbon diet.** For the basics of how to change the composition of meals (not their mode of preparation) in order to be climate friendly, and what effect size this has, see: Low-carbon diet.
- **Reducing meat consumption.** "Meat consumption needs to be reduced by up to 90% according to a 2018 study published in Nature." (source)
- **Better chewing.** It would be interesting to calculate the climate benefits of this, due to lower food use and lower greenhouse gas emissions from agriculture.
- **Hypocaloric diet.** A hypocaloric diet (1-0 diet, intermittent fasting etc.) is healthy, and it saves a net amount of food, and thus the emissions of producing that food.

4.3 Against food waste

Food waste and GHG emissions. “The food we waste is responsible for roughly 8 percent of global [GHG] emissions.” (source). Some more details: “The UN Food and Agriculture Organization collected data and found that by the time food reaches the consumer, 9% (160 million tons) goes uneaten and 10% is lost to overconsumption - meaning consumers ate more than the calorie intake requirement. Other aspects of losses surrounding dry matter came at each stage in the food system, the highest amount being from livestock production at 43.9%, transportation accounted for 18% and consumer waste accounting for 12.2% loss.” (source)

Avoiding food waste is a communal activity. That’s a major aspect of greener living that is possible in community, and less possible in small households. Because with more people, larger amounts of rescued food can be utilized, with a large commercial kitchen food can also be preserved easily etc.. On top, rescued food can be shared in the neighborhood, which makes urban living greener even for *others*.

Food preservation workshop:

- solar dehydrator
- canning and pressure canning equipment
- large collection of canning glasses
- fermenting equipment

Rescuing food is the best way to make an urban household carbon negative. Due to limited space and tools, urban households have not that many options to become carbon neutral or carbon negative. However, by rescuing more food than a household needs for own consumption and distributing that in the neighborhood, a household can easily become carbon negative because this activity lowers demand for food and thus avoids the emissions of producing more food. The same applies to other neighborhood services of resource re-use and recycling, but rescuing food is the most obvious.

5 Space

This is about the basic space utilization of a building, and the materials and technology to construct the shell of the building incl. its inner partitioning. Everything else that will be added to the building afterwards (for example insulation) is treated in the other sections.

5.1 Compact living

Compact living technology and innovations allow to shrink individual rooms without a loss of comfort or function. So evaluating this comes before deciding on the room layout of a building, because it will turn out that inhabitants will be comfortable with much smaller rooms, allowing to fit more people into the same building. That in turn saves emissions from space heating and embodied energy.

Space-Saving Furniture. This is about “tiny house furniture innovations” so that 20 people can live in a house meant for 10. As a side effect, such furniture can also be used to solve the (urban) housing crisis that young people experience in cities.

Compact storage. Storage is a major aspect of space utilization in households. So by storing only what is needed ("minimalism") and storing everything in a very compact manner, the same space can suffice for more people without loss of comfort. That translates into emission savings for heating, embodied emissions etc.. A few ideas for this:

- Create a storage system with stackable 60×40 cm Euro containers and use it in the whole building. Each box gets a unique number, and each storage location gets a name. Storage locations can be created in all kinds of odd spaces, including inclined areas under the roof and under stairs. Up to five boxes can be stored in a deep comaprtment in one line, to be extracted with a hook on a stick when needed. Use a database to record the contents and positions of boxes.
- Store clothing sorted by type in plastic bags, and the plastic bags in boxes. Do not fold or even iron clothes.
- Utilize all kind of odd spaces, such as under beds, on top of wardrobes etc.. Wardrobes should reach up to the ceiling and come with an attached ladder to reach to the higher compartments.

5.2 Communal living

The basic room layout and partitioning of a building determines most of its space use efficiency. In communal living setups, emissions from heating and embodied energy decrease linearly with an increasing number of people in the same space, so ecological communal living is about maximizing the number of people in the same space – within practical limits.

Avoiding apartments. If everyone has an own apartment and on top the communal spaces (party kitchen, courtyard, swimming pool etc.), it becomes more expensive per person, less space efficient and less resource efficient than the current standard family home or apartment. It can work well in social terms, though. But there seems to be a middle ground where apartments can be avoided: providing individual rooms with private bathrooms each, while all other spaces would be shared. Student housing in the UK and youth hostels are done similarly.

Floors as sub-structuring. In the Cent-vingt-trois communal living project in Brussels, floors emerged as a natural way to structure the space. Each floor had a certain dedication / specialty, for example children, receiving guests, or punk / anarchist aesthetics. The higher up the floor, the fewer random visitors it would get as there were no stairs – effectively allowing people to choose their level of privacy. People could move between floors, and that was the mechanism how the personalities of floors naturally emerged in the first place. This mechanism allowed people to live with people they like, and avoid people they don't like – which always happens, and is a larger problem in smaller communities where there is less space.

The Modern Dorm. It makes no sense to build, heat and clean complete rooms just for sleeping 8 hours a day. Instead, a different style of dorms could be great. Each person or couple would get their own "pod", with a curtain etc.. There would be mixed dorms for singles and perhaps even dorms for couples. Dorms would not be very large, but fit 6 people into a room that would usually sleep 2. This way, people can cluster in groups that like each other and are compatible (regarding snoring etc.). In exchange, dorm sleepers get access to a luxurious room that they can book by the hour without costs (for making love, when being sick etc.). Dorms would use pods in two layers and sound and light sucking material and shapes everywhere (against snoring etc.). Both the dorms and the pods themselves would also be heavily insulated so that ideally, dorms will heat themselves from the body heat of people inside.

5.3 Flexible spaces

Current houses (and the furniture available for them) are dominated by single-purpose rooms. Since inhabitants are only in one place at a time, this means that they move between different spaces and that all their spaces except one are unused at every point of time. Instead, a much more space-efficient approach is a single space that adapts to all uses just-in-time. That is not a comfortable solution with current technology as it would require too many conversions in a single day. However, a middle ground is achievable. Some ideas are provided below:

- **Office-and-party space.** An office and co-working space during the day that can be quickly converted into a party space at night. The coworking space would include good office equipment (incl. printers, a film plotter etc.). Also, a self-service coffee machine and coffee would be provided. Then, by flipping some furniture around, the space will transform into a multi-use space for parties, yoga sessions and the like.
- **Personal shelves, not personal rooms.** A mobile personal shelf can be used as the replacement of the current standard idea of an “own room”, which is totally a waste of space. Here, people don’t get own rooms in a communal living space, but own shelves. The shelves would have wheels and look like sack barrows with boxes on them, so they can be moved around in the house easily, including up and down stairs. This way, people can move between rooms in a few minutes, or store their shelf when leaving the house for a few days. Together, that enables a full utilization of the available space.

  In addition to the rolling shelf, there would be a communal storage room for other items, where everyone would have one or more lockable shelf compartments. They would be able to keep that as long-term storage even while not living in the house for a time. Even the mobile personal shelf itself can be locked in there.
- **Mobile spare beds.** Rooms typically have enough space to sleep more people when there is a need, but the limiting factor is usually the availability of beds. Instead, in a communal living setup there could be a storage of 10-20 mobile spare beds, using a system that allows compact folding and usage as single beds, double bed and bunk bed.

5.4 Layout against heat loss

Heated core. One of the largest energy saving options in communal living is combining the heated spaces of all inhabitants into one compact space. The surface area per volume is much lower then, so the heating costs are much lower. Note that this does not mean heating only one room – just that all heated rooms together must be next to each other and their hull should have a small surface relative to the volume (means, having a sphere or cube shape). For example, a cube shaped space in the center of the house can consist of 4-8 rooms belonging to different apartments on different levels of the building. The heated rooms would be bathrooms and a multi-use kitchen / living / office space.

Unheated periphery. Around this heated space, the non-heated rooms would be arranged, including bedrooms, storage rooms, workshop area etc.. They are kept warm-ish by the waste heat escaping through the walls of the heated space. Of course, the walls of the heated space would be well insulated, like outdoor walls. As the non-heated rooms would have the same insulation on the outside walls and at the walls of heated rooms, their temperature will be about halfway between the outside temperature and the temperature in heated rooms, so rarely lower than 10 °C in a central European winter.

A building that grows and shrinks on demand. Generalizing the concept discussed above, one could even organize rooms in a core and one or more shells so that all rooms are insulated against each other just as well as the house is insulated against the outside. Each room will then be “heated”, “unheated” or “semi-heated”, the latter being applicable for people with warm or heated clothing. Since all walls, inner and outer, are insulated to the same level, this means that the house can energetically shrink to become a small house, and grow again to a larger house, as needed. By concentrating the actively used space as close to the core as much as possible, the house will maintain a compact surface, which helps to lower heating demand. Because insulation material also has embodied energy and emissions, this makes only sense when the additional indoor insulation has very little of that – see section “Upcycled building insulation” for a solution.

Summer and winter living rooms. When enough space is available, it could be a good idea to have two living rooms: an unheated summertime living room that is made to be comfortable on hot days, and a cozy wintertime living room. After all, being comfortable with the same furniture and equipment year-round is only possible when the room has an artificially controlled climate – when trying to avoid or minimize this, it is obvious that different climates call for different rooms. The summertime living room could for example be attached to a rooftop terrace, and people would use it with their street clothes and shoes. In contrast, the wintertime living room would be meant to be used without shoes, as the floor and other surfaces would be meant to sit on, and would be covered in blankets and cushions. That room would be relatively small, have a cozy style and let people stay closer to each other – simply because a small space with many people is warmer than a large space with few people. The room itself would usually be unheated, but the waste heat from people and small heated spaces inside it would usually provide a room temperature of 14 °C or higher. It would feature cozy heated furniture such as a Japanese *kotatsu* table – a small, blanket-covered table with a heat source underneath where everyone puts their legs below.

5.5 Ecological indoor construction

It will be difficult to apply cob and other natural, upcycled or otherwise low-footprint building materials on the structural parts of buildings due to legal regulations and durability in outdoor conditions. However, all kinds of separation walls, thermal mass and sound insulation elements on the inside can be built from cob and other natural materials that "can be sourced in the backyard". This is esp. useful when the stories of a building only have structural outside walls and just pillars inside, and when the ceilings are durable enough to carry the additional weight of indoor cob walls.

Example techniques:

- **Indoor cob plastering.** This can easily be applied in urban living situations, both with respect to looks and practical considerations. See for example how it is used in this refurbishing project. Cob can usually be made from local soil on-site, as most soils contain a certain amount of clay that can be extracted.
- **Wattle and daub.** Can be used for indoor separation walls of varying thickness.
- **Papercrete.** Papercrete is a light and well-insulating material that can be locally made into blocks or poured into whole walls with just trash paper and concrete as its ingredients. To make it more sustainable, one could experiment with replacing a part of its portland cement content with alternative cement.

That should be possible, as papercrete walls are usually not made to be load-bearing anyway.

Literature: (all works are available online in open access fashion)

- **Modern Masonry Natural Stone and Clay Products.** 1956. 164 pages.
- **Handbook for building homes of earth.** 1980. 159 pages.
- **Stone: An Introduction.** 149 pages. with everything you ever wanted and didn't want to know about using stone as a building material, how to work it etc…
- **Bamboo as a building material.** 1982. 52 pages.
- **Building stone, lathing, plastering, and tiling, common brickwork, ornamental brickwork and terra cotta, lighting fixtures, use and design of lighting fixtures, architectural design.** 1909. 496 pages.

5.6 Efficiencies of shabby chic

Build something old, not something new. Trying a conversion to make an old space look new is difficult, esp. on a budget. But trying to make an old space look old but great is much simpler and cheaper. It just needs old materials and good "shabby chic" taste. This is similar to the approach of building maintenance over new construction, just that it is here extended beyond the building and to the interior. The idea is to "keep the old look and work well", so that there is never ever a need for "renovation". In fact, some old buildings with proper, nicely designed and thought-through (but not costly or carbon intensive) interior feel way more homely than modern, mass manufactured buildings with their white, minimalist aesthetics. How can a practice of communal living be built around this idea? How could that include household-size elements of a circular economy (basically "throwing nothing away")? That also includes household-level production from raw materials that would usually be thrown away. It would extend to all areas of life, including a "shabby chic" clothing style. And it is not at all clear at the moment what that even means.

Inspirations from around the world. In traditional Japanese aesthetics, *wabi-sabi*, "the beauty of imperfection", is about products made in a shabby chic style from the start. And the Japanese technique of *kintsugi* is about repairing broken ceramic vessels with gold, and can be seen as a celebration of breakage and repair as a part of the lifetime of objects.

5.7 Upcycled and DIY furniture

Most modern furniture items are still very simple products without moving parts and without difficult requirements. They can be made from a multitude of discarded materials with hand tools and creativity, and if done right can provide an artful, aesthetically pleasing furniture system that (because it's upcycled) has zero embodied emissions. This kind of DIY furniture is also very suitable for households still experimenting with ecological living as these items can be modified much easier than commercial "high finish" furniture items – and while experimenting, changes are required all the time.

Some ideas for upcycled furniture are provided below:

Cardboard furniture system. This is zero-footprint furniture by combining trashed cardboard (glued together into boards of 1-5 cm thickness) and 3D printed parts as connectors and accessories. The furniture "boards" can be cut with woodworking tools incl. a tablesaw. Only 2D cutting and 3D printing would be needed, which means that this furniture can be produced by anyone. Since 3D printed parts can be recycled into 3D printing filament, and since all 3D printing and tool use can be done with locally produced solar electricity, and since a city always has more than enough trashed cardboard around, all this furniture can be produced at zero cost. This allows to produce it on demand, even for single occasions. To be a system, it would be based on (mostly) standard 3D printed connector parts (for inspiration, see PlayWood, https://www.playwood.it/). And it would use cardboard sheet material "boards" in standard thicknesses of 0.5, 1, 2 and 4 cm only, which would be produced in advance and stocked in larger amounts in the house.

Furniture from urban bamboo. Bamboo is a material that with significant potential to reduce GHG emissions (see). The idea is to grow enough bamboo around the house and in the local neighborhood for all structural needs inside the house. All furniture etc. would be created and re-created with this bamboo and household tools, and at the end of its lifetime bamboo furniture would be composted or burned in-house. Basically, grow timber bamboo around all walls of the house. The bamboos would be ca. 50 cm away from the wall and grow between the wall and bars surrounding the wall in ca. 70 cm distance at the level of every story. This prevents the bamboos from falling over in case of storms etc.. If necessary, the bamboos would be grown in containers to prevent their roots from interfering with building walls etc..

5.8 Noise management

Ideally, the same space would be used as both living area, kitchen area and working are (for office work etc.) combined, because that reduces the amount of required heated space in the building, and of space (and associated embodied energy) in total. However, in compact and esp. communal living spaces, space is no longer available as a way to counter noise problems. For example, if your partner snores, just having separate sleeping rooms is not an option.

Here are various ways to try for managing noise without needing more space:

- **Earplugs.** These are a good solution – consider always carrying a few reusable silicone earplugs in your jacket. They also help in public transport, which is very noisy as it needs to be designed for the hard of hearing. So if you have sensitive ears, plop in the plugs and arrive much more relaxed.
- **Headphone earplugs.** Similarly, tight-sealing headphone earplugs work well to drown out annoying noises in public transport, or if you sleep close to someone who snores, or if there is a lot of traffic where you sleep. For sleep, even damaged earplugs where only one side works are fine (you can cut away the other side). Make sure you don’t damage the earplugs’ wire or the connected MP3 player or smartphone. That can be a challenge at night, so it may be justified to look for some well sealing, used wireless earplugs, even if their battery is weak.
- **Noise-canceling headsets.** People who need to concentrate (to work at the computer etc.) would use active noise-canceling headsets, including with appropriate music to drown the rest of the noises
- **Signaling mechanisms.** In communal spaces, people would be able to register the need for some quietness, and this would be signaled with colored lamp or similar in the middle of the room; in response, the others would not speak louder than necessary.
- **Noise-canceling furniture.** People who are on the phone or in talks with 2-4 people in the room would use specially designed noise-canceling tables, equipped with nice looking noise-canceling cones.
- **Low-noise rooms.** Here, a lot of noise-canceling cones and architectural elements would be distributed around the room, the idea being that people don't really hear each other when being further than 5 m from each other.

- **Don’t yell, message.** In communal spaces, people would wear headsets to send voice messages to each other rather than screaming through the room

6 Heating

6.1 Upcycled building insulation

Insulation saves on heating energy, but is also a major source of a building's embodied greenhouse gas emissions due to the energy intensive manufacturing process. The more houses are heated with sustainably produced heat, the higher the proportion of emissions embodied in insulation. For a fully carbon-neutral house, its insulation also has to be carbon neutral.

Fortunately, many everyday materials can be reused as insulation. High-tech insulation with a very low thermal conductivity is not "better" in an absolute sense: the exact same insulation effect can be achieved with thicker material of higher thermal conductivity, and the lost space can be easily recovered with better space utilization. Now if a material reused as insulation would otherwise have been incinerated of landfilled, using it as insulation is basically emission-free.

Examples of zero-emission insulation. Below are several options for such materials.

- **Used building insulation material.** This includes glass wool, rock wool and expanded polystyrene. Usually this material is landfilled or incinerated when a building is demolished, so its further use is zero-emission. Lifecycle analysis shows that the energy needed for building construction and for heating the building over its lifetime are about the same for modern buildings; for very low-energy buildings heating energy demand will be somewhat lower, in exchange for somewhat higher energy embodied in construction (source). This means that very significant energy savings can be made by reusing existing building materials. In contrast to industrial recycling processes, re-use needs very low additional energy input. One of the materials that is simplest to re-use is glass wool and rock wool because damages sheet material can be processes into loose flakes, similar to blow-in glass wool or rock wool material.
- **Expanded polystyrene.** Polystyrene foam from old buildings, packaging etc. is typically simply burned, but it can easily be remanufactured by gluing it into new blocks with a simple press.

- **Fibers and fabric from old clothes.** They can be stuffed into containers that are then used as insulation blocks indoors. Or they can be manufactured into fiber mats and blocks by disintegrating the fabric first into fibrous material.
- **Plastic bags and plastic film.** Plastic bags are still a fact of life, and will be for some time. Also, plastic films in more general are a waste product from packaging etc.. Blocks of slightly compressed, crumpled plastic bags are probably good insulators: they are light, cheap, trap a lot of air in small spaces (which is how insulation works), do not rot, do not let air pass through but are also not completely airtight. Also plastic itself has a relatively low thermal conductivity – blocks made from crumpled aluminium foil would perform worse.
- **PU insulation from old refrigerators.** Refrigerators contain a lot of PU insulation foam, but it is currently not recycled. It makes for a very good building wall insulator, though (nearly twice as good as rockwool), so it makes sense to use it for that purpose in buildings. First, obtain it from waste collection stations by extracting it from fridges brought there. Then use a semi-automatic setup to cut the insulation into cuboid shapes of compatible sizes, using as much of the fridge insulation as possible. Finally, glue these small blocks together to insulation elements of any size.
- **Papier-mâché and papercrete insulation blocks.** Pressed into a form with air chambers. Applied indoors by building walls from these building blocks. It is probably also possible to create papier-mâché blocks with a porous structure for better insulation, by mixing them with a baking agent / leavening agent and heating the block while it is still wet.
- **Corrugated cardboard insulation blocks.** Just collect corrugated cardboard from shipments, from neighbors etc. and glue the layers together with wallpaper glue. Powertools can help to shape the blocks so that they lock together like puzzle pieces. For example, massive 60×40×40 cm blocks can be glued from many layers of corrugated cardboard, and in such a way that they fit together like puzzle pieces into the room they are meant for. (This will need some 3D CAD, scripting some own software, a laser cutter or CNC mill, and a station with registration sticks to assemble the pieces.)

Improving insulation over time. An interesting aspect of reusing material as insulation is that a household can improve its insulation over time by simply collecting and using the old clothing, plastic bags etc. that would otherwise be thrown away. After 10 years, the house might have a 1 m layer of insulation all around.

Fire safety. The main issue with these insulation materials is of course fire safety, but that is manageable. For example by using non-flammable boxes to contain the material, and by using these blocks only indoors, together with a good system of detecting and extinguishing fires early.

Usage as indoor insulation. Basically all existing projects for energetic retrofitting add insulation layers to the outside of the house. That is expensive, as the material must be weatherproof. However, there is so much unused building stock and the area per person is also so much larger than in the past that it is not necessary at all to add to the outside – it's ok when the rooms shrink because of adding insulation. That is much, much cheaper, as the same outer shell of the house can still be used for weather protection, and much cheaper materials can be used inside.

So it is recommendable to use the experimental materials listed above as insulation on the inside of a building, until enough experience with their behavior and use has been obtained. It allows better monitoring and quick interventions if something goes wrong (for example, if condensation develops). This also solves the problem how to use these “unlicenced” DIY materials for building insulation. Namely: simply use them as "furniture" inside the rooms, without installing them in a fixed way. Then, nobody can prohibit their use. Ideally, make them indeed be furniture, by integrating shelf space etc. into the inside facing side of the insulation blocks.

Condensation issues. Condensation is the main challenge when using indoor insulation as proposed above. However, there are also multiple unexplored ways of dealing with this. Condensation would develop on the insides of the outer walls when warmer, humid air comes in contact with that wall and cools below its condensation point. To prevent that from happening, a 5 cm gap between the outer walls and the indoor insulation is a good idea. This allows to monitor relative humidity of the air inside and keep that low enough by one of the following methods:

- Regularly circulating dry air behind the wall, for example by operating a closed-cycle electric dehumidifier.
- Using cartridges of chemical drying agent embedded into the indoor insulation that keep the air behind it dry. Probably one would use calcium chloride cartridges and make both these cartridges and the brine container with

condensate accessible from the inside of the rooms. Exchanging these would only necessary every 1-3 years and the time to do so would easily be recognizable from the fill mark of the condensate container, visible from inside the room.

- Circulating cold outside air inside that gap, which can only warm up there and thus will never lead to condensation. That effectively removes the additional insulating properties of the outer walls, so that their sole function would be weather protection and providing the building structure. However, the loss of insulation is not severe for uninsulated outside walls and can be compensated by adding some more indoor insulation.

6.2 Insulated indoor clothing

When they can choose, people prefer a warm room and thin clothing over a cooler room and warm clothing. This seems to be because warm clothing is often heavy, uncomfortable and movement inhibiting.

It does not have to be like this. Heated clothing is the most extreme solution to this challenge, but before going that way, a new style of indoor clothing can go a long way. Even with just one light down jacket and a shawl, comfortable desk work is permanently possible down to 14.5 °C (data point by @matthias). With highly optimized but unheated clothing, it should be comfortable down to 10 °C, perhaps even to 8 °C.

A few design hints from personal experiments include:

- The clothing should be very light and very compressible, because that makes it not inhibit any movements. Down clothing with very light ripstop fabric is so far the best choice, both for jackets and trousers.
- A shawl is a surprisingly effective piece of clothing.
- Footwear deserves special attention as the feet are usually the first part of the body to start feeling cold, both because the feet have low blood circulation esp. at rest, and because air close to the floor is usually the coldest air in the room. There are some aerogel insulated outdoor shoes produced commercially. An aerogel insulated indoor shoe could become a well-loved type of clothing, and lends itself to DIY production.

As a side benefit, it may be that resistance against respiratory infections is higher for people who are acclimatized to inhaling cool air because they live in cool rooms all the time. This is just anecdotal evidence for now (by @matthias) but there might be studies or other data to confirm it.

Engineering clothing like insulation. The right approach for creating better clothing for cold environments is to perceive clothing as insulation and to apply all the tools and calculations to it that are so far only applied to houses, including:

- thermal imaging to determine the total energy lost to the environment
- fuel consumption tracking, by measuring the CO2 content and volume of every breath before and after breathing (helps to deal with the metabolic base load that is different at different times of the day and night cycle)
- determining thermal conductivity values of clothing
- dealing with convective heat losses by limiting the amount of warm air that can escape at the neck, at the sleeves and from uncovered skin

6.3 Heated clothing

For grid-connected indoor environments, using electrically heated clothing (switching to an electricity supplier that provides renewable energy) is the simplest way to provide heating that is both ecologically and financially sustainable. Heating whole rooms with grid electricity would, on the other hand, be expensive.

Next to small heated spaces, heated clothing is the second major way of avoiding space heating – it is even more experimental and “extreme”, though. Heated clothes exist for outdoor activities, but nearly all of them use batteries (which is uneconomical for permanent use) or use catalytic fuel burners (which is inadequate for indoor use). Our initial ideas for R&D to solve these challenges include the following engineering proposals and extensions:

Engineering proposals

IR-transparent radiatively heated clothing. The idea is to heat the body with short-wave IR (like the IR part of sunlight, emitted by items 300-800 °C hot) and to keep the long-wave IR that results from this (emitted by the body at a surface temperature of 25-45 °C). So we need insulation that is transparent for short-wave IR and intransparent for long-wave IR. For example black underwear clothing on top of which one wears a kind of bubble wrap clothing form plastic film that has these desired properties.

Inductively heated clothing. Heated clothing could be heated inductively, with metal in the shoesoles or carbon fiber in the trousers (and then induction sources in the seat surface and backrest). This allows to even transmit the energy through a layer of insulation. Instead of direct inductive heating (as in an induction stove), induction can also be used to transmit electricity wirelessly, and with that power the clothing and even charge a thermal storage and / or battery. So when sitting on a chair or armchair, the bottom and / or backrest would have induction loops. And even the floor can have induction loops inside, working while standing in certain locations (in the kitchen etc.).

Heat-pump heated clothing. Electrically heated clothing is nice because there are no exhaust fumes to deal with, but battery storage is expensive and also not enough to provide a full day of runtime for heated clothing. However, the heating value of electrical energy can be raised by 300-400% by employing a heat pump. For a heating output of 100 W (the same as the body's own average heat generation), one would then only need 25-33 W of electrical power, compared to 100 W for resistive heating. This could make batteries light and cheap enough to power heated clothing.

Electrically heated clothing with nickel-iron battery. Batteries can be used safely indoors for heated clothing, as there are no explosion hazards and no toxic fumes. The only reason against them is that they degrade, which means the cost of electricity (and its environmental cost) is high. That's not true however when using nickel-iron batteries, as these do not degrade. These batteries are relatively heavy compared to lithium-ion batteries (about three times as heavy), but for indoor use that is acceptable, esp. when using energy-efficient heated clothing based on heat pump technology. Also, they are still about three times lighter than supercaps, the only other way to store electricity in non-degrading storage. One would simply exchange the battery with another one after about two hours of use, and every room would have a battery swap and charging station in reach. Also, when doing seated work, one would attach an electrical quick connector or even be connected automatically (see above), which charges the battery and extends the runtime considerably. So during most days, one would not have to exchange the battery pack at all.

6 Heating

Heat buffer heated clothing. Water is a harmless chemical with a very high heat capacity (4180 J/(kg*K)) and a suitable choice for a thermal mass “heat battery” to extend the usage time of heated clothing without any need for batteries. To create a heat buffer that lasts 3 hours with an output of 100 W (the same as the human body at rest and probably suitable for most use cases of heated clothing), one would need 300 Wh of stored energy in heat usable for body heating, here defined as heat >30 °C. That requires an amount of ~3.7 l of water at 100 °C (see). It seems possible to integrate these 3.7 kg of hot water into clothing comfortably, though that might also be the upper limit. Anyway, 3 hours of mobile operation is quite a comfortable solution already. The water would be re-heated whenever an electrical connection is available (see above) and could also be exchanged within 10-20 seconds with a quick connector hose attached to a reservoir. This is a much faster additional option compared to the 6-10 minutes that would be required for electrical re-heating with SELV electricity.

The innovation here is heated clothing without being permanently tethered to an electricity outlet, and also without using batteries (which would make a kWh of electricity even more expensive). The idea is to carry a small vacuum insulated stainless steel metal can around that is filled with material with a high heat capacity and heated to a high temperature. Fireclay or chrome-nickel steel plates are useful here. When connecting a cable to the grid, the material is heated within 30 seconds, and that heat should then be able to power the heated clothing for another 60-80 minutes. The heated clothing system would then have a battery, fans and perhaps water circulation to distribute that warmth in the clothing over time. During stationery work or activities, one would keep the charging cable plugged in, and the heat battery would charge much slower (and after that only take the "maintenance charge power") to prevent heavy short-time loads on the grid.

Doing the numbers: Assuming 20 seconds and 30 minutes and a heat output of the heated clothing of 100 W (doubling the body's heat output), 50 Wh would have to be provided in 20 s, which means a power rating of 9 kW (qalc "(50 Wh/20 s) to W"). That's possible with three-phase electricity in households (up to 3 * 3.5 kW = 10.5 kW), but might be difficult to integrate into a device with a small form factor. A charging time of 60 seconds at 3 kW seems more appropriate. Now when using steel (such as stainless steel) at 900 K over ambient temperature, the amount of material needed to store these 50 Wh would be 421 g (see qalc "1 / (475 J/(kg*K) / 50 Wh * 900 K) to g"). Water can only be used to 100 °C or maybe 180 °C in a pressure vessel, but has a much higher heat capacity. Assuming 100 °C (which is pressureless water and thus safe) means 70 °C over skin temperature, so the mass of water needed would be 615 g (see qalc "1 / (4180 J/(kg*K) / 50 Wh * 70 K) to g").

As pressureless water does not pose the fire and burn hazards of steel at 900 °C, this seems to be the route to go. With a proper design, up to 4 kg of water could be incorporated into the clothing itself while keeping it comfortable. That would cover up to 3.5 hours at 100 W heat output. For example, a vest with half-length arms made from a kind of foam that soaks up the hot water and has aerogel insulation on the inside and outside to store the heat and only slowly release it. Assuming a use for 16 hours a day at 100 W average heat output, that would amount to 1.6 kWh of energy per day, or about 1.6 kWh * 180 days = 288 kWh per heating period. At 0.30 EUR/kWh, that would be 86 EUR per person in heating costs. In pratice in a moderate climate, it could be half that as one would not need the full output during the full wake period of the day.

In other circumstances, such as off-grid households, the recharging would be done by burning carbon-neutral fuel such as ethanol, biogas, woodgas or wood pellets. Since the fuel burner will not be permanently active and can be placed in a fixed position to vent outdoors, there is no problem with indoor use here. To recharge, the cold water in the clothing would be exchanged with hot water, which can be done very fast. Since this allows to buffer hot water in an insulated vessel for future uses, it also allows to use a very small (cheap) burner to heat that water. It would not have to be much more than 100 W in output, as that is the heat output needed.

To make the use of the heated clothing comfortable, it can be integrated with some of the habits of living, esp. getting meals and snacks. So when going from the workshop downstairs to have a coffee, you recharge the heat battery as well.

Hydrogen heated clothing. Hydrogen has the advantage that its combustion product is just harmless water – and some nitrous oxides, but that can probably be eliminated when using catalytic conversion rather than an open flame. That in principle allows to use it indoors. Since "charging points" are easily available indoors, a hydrogen tank with limited storage (such as compressed gas at 20 bars) is acceptable. One would have to recharge every 2-3 hours for a few seconds. Catalytic conversion rather than an open flame is also preferable for fire safety and explosion safety of the hydrogen powered device. It will generate low-temperature heat, but that is acceptable for this purpose.

Ethanol heated clothing for outdoor use. For outdoor use away from the house, we would like a longer mobile use time, ideally a full day awake (16-20 hours). This becomes possible because outdoor use allows burning fuel safely. Ethanol produced from renewable resources is a suitable, energy dense and safe fuel for this purpose. A mobile burner unit would be carried as a backpack or detachable handbag and would re-heat the 3.7 l of hot water whenever necessary. This is not strictly about ecological living, but a way to transform the human relation to outdoor space as a nice side effect: suddenly, it will be comfortable to have an outdoor dinner in winter, to cook outdoors etc.. This in turn might prompt other lifestyle adjustments: why have a large living room when the outdoor area is now comfortable even in the midst of winter?

Possible extensions

Electrical quick connectors. Many activities in the home are stationery, including screen work, kitchen work and resting / sleeping. Electrically heated clothing that is connected to a (very safe!) SELV DC energy supply with a spiral cable and magnetic tear-away quick connector could be a comfortable option. The human body does not immediately feel cold when "turning off the heating", but rather has enough stored heat for staying comfortable for 1-1.5 hours in cool (8-10°C) environments, given suitable clothing. This means that only an occasional connection to electricity is enough to keep warm with heated clothing.

Automatic connection. For indoor use, electrically heated clothing is a good idea but it won't achieve widespread adoption if (1) its use is expensive due to battery power or (2) people have to permanently remember to connect and disconnect a cable when sitting down resp. standing up. For that reason, automatic connection is better than the electrical quick connectors proposed above, and might be realized in one or more of the following ways:

- inductive connection, like of an inductive charger, using material embedded in the contact surface of a chair and the clothing
- inductive connection, but with material embedded into the floor / carpet and into the shoes
- as before, but using a metal contact connection so that a low-voltage connection is automatically established between contacts in the floor and shoes resp. in the chair and trousers after an electronic system determined contact

pairs that will not lead to short-circuiting; as all contacts are powerless before this automated test is done, the system is protected against short-circuiting from dropping metal objects on the contacts etc.

Air pre-heating collar. Heated clothing on its own cannot completely replace space heating, as it runs into a limit at the temperature where cold air becomes too cold to breathe permanently. That limit is about 15 °C, as air is becoming uncomfortable / irritating to the throat then. With a shawl, that limit can be pushed to about 12.5 °C. Now the idea is here to create a new piece of clothing that supplies pre-heated air to the nose for breathing in. With such a device that would pre-heat air to 15 °C and together with heated clothing one might be comfortable in rooms down to 0 °C or even below, which means no space heating is needed at all anymore, with the exception of the bathroom. The new limit will probably be when the hands are getting too cold and using heated gloves is not possible due to the nature of the work.

The device would look a bit like a shawl with an integrated fan. It would supply the air with the fan not constantly, but only when one breathes in, and would run the fan in reverse to take in the exhale air in order to extract heat from it for pre-heating in the inhale air. An air-air heat exchanger would be used for this mechanism, to avoid providing very moist air for inhaling. Perhaps 10 W of pre-heating would be needed in addition, depending on temperature. This can be provided with a catalytic pocket stove, with a small ethanol or LPG flame, or electrically. Even when provided electrically from a battery, it would be possible to create a device with a full day of runtime. Obviously, when this device is used in combination with heated clothing, then it can be water heated or electrically heated (with a cable connection), the same way as the heated clothing itself. Also, a pulsing or even constant flow of warm air is all that's needed, as there are no extreme requirements for energy conservation in such a situation.

6.4 Small heated spaces

Small heated spaces are alternatives to heating complete rooms or even the complete building. Rather, one would just heat a small space inside a room. These small heated spaces can take many forms, and can embody feelings of cozyness and hygge, providing comfort through the cold part of the year. Obviously, proper design is important to achieve this and make people love their small heated spaces.

Examples. Small heated spaces can take many forms, and most of them are unexplored. Example ideas include:

- a “bed cave”
- an enclosed screen workspace inside a larger office
- an enclosed kitchen corner, for example using ceiling-high insulated glass walls as separation from the living area
- heated Japanese *kotatsu* table for the living room
- heated office chair
- heated armchair, complete with a plushy cushion, blanket, warm shoes or footrest, into which one can completely disappear and that will then insulate the body
- heated dining space, perhaps scalable to the amount of people taking part in a meal
- heated bed, convertible between winter (cave style with heating) and summer (open style) modes
- water-heated mattress, as an alternative to an enclosed heated bed; the mattress would be connected to the hot water line of the space heating system and thus be more energy efficient than existing, resistively heated electrical blankets or mattresses
- heated computer corner, with the computer (~20 W) and human body (~100 W) heating up the space
- heated small bathroom, distinct from a larger bathroom with shower etc. that would only be heated on demand
- heated shower cabin, which avoids the need to heat the whole bathroom

Small spaces heated by usage. The architecture and thermodynamics of such small indoor spaces is largely unexplored. Some can probably be made self-heating – for example, a comfortable “dining cave” might be heated by the presence of people (100 W each) and pots of hot food. A glass-enclosed kitchen corner is pretty surely self-heating by its use. A superinsulated small living room will be self-heating (to, say, a comfortable 17 °C) when enough people are present inside and the outside environment is not too cold.

Small spaces heated with waste heat. Electric and electronic devices in a household produce a lot of waste heat, because ultimately all power ends up as heat. For example, the average German citizen using 6.5 kWh of electrical energy per day translates to 6.5 kWh of internal heat gains of the building per day. For comparison, a small space of 4×2×2 m with one person inside and 10 cm PU foam insulation all around will require an average of 8.7 kWh/day through the German winter for an average inside temperature of 14 °C (experiments by @matthias). So the electrical waste heat of two people's consumption – a power output of (2 × 6.5 kWh) / 24 h = 540 W – would be already enough to keep such a space at a comfortable room temperature. To make this possible, the waste heat of electrical devices would have to be concentrated in such spaces. This is possible to an extent, for example by letting the back of the fridge and freezer face into that space, and by locating the wifi router etc. there as well. Computers are a good case actually: their waste heat is just waste in data centers, but the combination of fast Internet connections, data efficient websites and CDNs makes it possible to self-house a web server, using its waste heat as space heating. Similarly, the waste heat from shower water could be directly used for keeping a small heated space warm, by routing the shower water to a temporary storage tank inside that space (see section "wastewater heat recovery" for details).

Small spaces heated with heat pumps. Air source heat pumps inside the small space that take their heat from the enclosing room are an efficient way to provide the heating: their air source will be air at 10 °C or warmer, at which temperature heat pumps are pretty efficient. A cheap and DIY solution is to place a fridge into the small heated space, and to circulate air between the surrounding space and the inside of the fridge using two hoses and small fans. A fridge is a heat pump and will heat up the small space with its "waste heat", extracted from the air circulating in it. This basically shovels the heat back that escaped from the small space into the surrounding room, which is how electric efficiencies of 250-350% are reached, compared to 100% for electric resistance heating. A Japanese *kotatsu* table with a heat pump as its heat source for example would be an interesting combination of old and new technology, saving two thirds of electrical energy compared to the current versions which are heated with an electrical resistor.

Saving 75% of heating energy with small heated spaces. Heating is currently one of the largest sources of greenhouse gas emissions, both inside buildings and as a fraction of global emissions (source). Lowering the indoor temperature has major impacts on the heating energy use: for example, a detailed computer modeling study based on the UK housing stock estimates that lowering the thermostat setting from 19 °C to 18 °C will result in 13% savings of space heating energy (source). The same study shows an almost linear correlation: lowering the indoor temperature by 2 °C will lead to 25% savings of space heating energy. Also note that the amount of energy savings per degree change in room temperature varies considerably between buildings – to determine it experimentally for one building, see here.

Now the above idea of *only* heating the small heated spaces will probably result in an indoor temperature outside of these small spaces of about 13 °C during the heating season. It cannot be much lower, as 13 °C is close to a lower bound for air that is still comfortable and healthy even under prolonged exposure and with the body at rest. That's a reduction of 6 °C compared to a usual 19 °C room temperature, and would lead to expected savings of 75% of heating energy, still assuming a linear relationship. A 75% reduction in space heating energy is a huge amount, given that space heating takes up the largest amount of energy and on average still uses the largest amount of fossil fuels in a building. Compared with other energy-saving behavior adaptations, it saves more than 11 times as much energy than the next best one that is not related to space heating (namely "Install water efficient shower head and use twice every day", see here).

Additional savings of embodied energy. Finally, there is an additional major energy saving related to the embodied energy of a building: manufacturing insulation material is energy intensive, and much less of it is needed when providing small heated spaces inside non-insulated larger spaces. Also, the insulation for small heated spaces can be made from salvaged materials as it does not have to withstand outdoor conditions for years. For example, paper, cardboard, crumpled plastic bags etc. are good insulation material and represent zero embodied energy when they are recovered from waste material.

6.5 Small interventions for heating efficiency

- **Room temperature of 14 °C.** It may not be this exact temperature for everyone, but it turns out (from initial experiments by @matthias) that with suitable clothing, something around this temperature is perfectly comfortable even for seated work. It may be that the human body needs a few weeks to acclimatize. In addition, you probably need a solution for humidity management to prevent issues with condensation and mold.

- **Anti-draught measures.** The building should be tightened against draughts of cold air as much as possible. There are ways to measure how tight a building is by inducing slight overpressure with a large fan.
- **Focusing on windows.** "According to the U.S. Department of Energy, heat that either escapes or enters windows accounts for roughly 30 percent of the energy used to heat and cool buildings." (source). A simple and effective intervention are for example insulation blocks from polyurethane or polystyrene foam that are placed into the window cavities of unused windows from the inside, and of all windows after dark. The insulation blocks would be equipped with a bag of rechargeable drying agent (as available for cars) in a pouch on the side facing the window pane, preventing any issues with condensation and mould problems in that area.

6.6 Seasonal heat storage

Ground source or air source heat pumps are the state of the art for emission-free space heating. Here, "Test results [of the coefficient of performance] of the best systems are around 4.5. When measuring installed units over a whole season and accounting for the energy needed to pump water through the piping systems, seasonal COP's are around 3.5 or less." (source). This relates to the European standard test conditions of 0 °C source and 35 °C sink temperature.

In comparison, seasonal thermal energy storage with a combination of water tanks and boreholes already provides a seasonal coefficient of performance of 27, also accounting for all pumping energy (source, p. 5, using data for years 7-10 where the system was fully charged). So for every unit of electrical energy, BTES provides 770% as much heat as state-of-the-art ground source heat pumps! Even the theoretical maximum for heat pumps under the above standard test conditions is just a COP of 8.8 (source).

The Drake Landing Solar Community system of water tanks and boreholes used as an example here provided on average 96% of all space heating from solar energy (source, p. 5). As it works with just pumps and no heat pumps at all, this is a DIY friendly and simple system. Also, as it is the first system of its kind, so it certainly has plenty of room for cost savings and further optimization, all of which can be pioneered in urban ecological living projects. During the 10 year runtime since the start of that project they were already able to lower the pumping energy requirements considerably: “The main strategy to reduce power consumption has been to increase the set temperature differential through the glycol loop, which leads to lower flow rates and pump speed. […] With negligible impact on collector annual efficiency, the electricity savings are calculate[d] to be approximately 50% of the amount used with the original control strategy.” (source, p. 7). Their glycol loop needs 33.5% of their total pumping energy, so this equates to 16.75% total savings for pump electricity.

Another possible optimization concerns fully solar powered single-building systems. It seems simple to achieve 100% solar fraction continuously in a system that only serves one household. The reason that natural gas post-heating was sometimes needed in the Drake Landing project is that, depending on outside temperature, a heat fluid temperature of up to 55 °C was required, which might not be available from the BTES. However, the BTES certainly was able to provide 30 °C water, and that can be used for floor and wall heating systems in a single building that is close to a BTES in its cellar or backyard. It is just not economic to dimension all the Drake Landing district heating piping for 30 °C water to be enough even on the coldest days – adapting the fluid temperature rather than the pipe dimensions is more economic there, where much more pipework is involved.

Regarding the charge / discharge efficiency of borehole thermal energy storage:

> Reported BTES round-trip efficiency [of 36-41%] is relatively low at Drake Landing due to high groundwater flow However, other studies have reported BTES efficiencies of 80–90%. Thus, proper site assessment regarding groundwater flow is important to promote higher efficiencies. Seibertz et al. determined that monitoring of cooling behavior from thermal gradients makes it possible to identify high ground-water flow zones using a decay time comparison. (source)

In zones of high ground water flow, BTES efficiency might be increased by underground dams, which can be as simple as burying a vertical layer of water impermeable clay around the borehole site, or simply one wall of that on the upstream side of the ground water flow. Alternatively, clay or silt could be injected in a ring of boreholes under high pressures to make the area more impermeable to groundwater flow. Or simply use all boreholes also for groundwater infiltration – after a few years and esp. with water rich in silt or clay, infiltration will no longer occur as the are around the borehole has been made water impermeable due to the silt and clay infiltration.

6.7 Seasonal heat storage with ASHP charging

> :bulb: This is a major, unexplored innovation on top of the established seasonal thermal energy storage technology (presented here). It makes heating all winter with solar energy at least 46% cheaper than natural gas. So we explore this idea in detail in this dedicated section.

The concept: charging with photovoltaics and heat pumps. The idea is here to build a seasonal thermal energy storage system that is charged in summer with photovoltaics powered heat pumps and discharged in winter without heat pumps, by running warm water directly through radiators in the building.

In contrast, all major seasonal energy storage plants (list, p. 11) feature one or both of the following systems: solar thermal collector panels to charge the heat storage in summer, and heat pumps to assist with extracting heat in winter. Plants that only use heat pumps are called "passive", as they rely on the natural heat of the ground, slowly conducted from depth. In contrast, the Drake Landing Solar Community (DLSC) is one of the few large-scale systems using only solar thermal panels for charging and no heat pumps for extraction.

The reason why the concept proposed here is so far unexplored is probably because both heat pumps and photovoltaic electricity only became cheap enough since about 2015 to be able to compete with solar thermal collectors the way shown here.

Cost comparison. The final decision for or against a new energy technology is, sadly, often purely financial: renewable energy would be much more widespread if it could compete with fossil fuel cost-wise. For heating, natural gas is the cheapest available fossil fuel option, and here the above concept provides a breakthrough 47% or more cost reduction compared to natural gas. The calculation below uses gas and electricity prices for Germany in 2019.

- **Ground-source heat pump: 0.091 EUR/kWh.** This is the most efficient storage-less way to use a heat pump. The calculation is based on 0.32 EUR/kWh grid electricity prices and using a heat pump with a COP of 3.5, which accounts for water pumping energy etc. already: 0.32 EUR / (1 kWh * 3.5) = 0.091 EUR/kWh.
- **Natural gas: 0.063 EUR/kWh.** This is simply the consumer price for natural gas in Germany in 2019 (source). Space heating costs will be somewhat higher as gas furnaces have an efficiency of 95-98% and some electricity is needed for pumping. This is neglected here.

- **Heat storage charged with PV + heat-pump: <0.034 EUR/kWh.** The system converts 1 kWh locally produced photovoltaics electricity in summer to 3.5 kWh heat using a heat pump and stores it in the seasonal thermal energy storage. From that, 2.8 kWh is extracted again in winter, assuming a high but realistic 80% charge/discharge efficiency. The upper limit for the production cost of 1 kWh PV electricity is 0.0959 EUR, as that is the, supposedly profitable, fixed purchase price obtainable in Germany starting 2020-01-01 from selling PV electricity from plants sized 10-40 kWp (source). This yields a cost of heating of 0.0959 EUR / 2.8 kWh = 0.034 EUR/kWh, representing a cost reduction of 1 - (0.034 EUR/kWh / 0.063 EUR/kWh) = 46% compared to natural gas and of 63% compared to ground source heat pumps operated with grid electricity.

Additional cost saving options. Obviously, the calculations above do not account for the initial investments for heat pump and storage system. However, these costs will decrease as the technology matures, and also by extending the lifetime of the technology. There are also additional cost savings listed below that decrease cost further, so that the idea is probably financially competitive with natural gas given the current state of technology. A more detailed analysis is still needed.

- **Avoiding AC conversion.** Additional cost reductions can be realized by running the heat pumps on direct solar DC electricity. To adapt to available energy supply, heat pumps would either run at variable speed similar to water pumps that are already available for this purpose, or multiple heat pumps would run in parallel to scale consumption with production. This avoids the investment in inverters and the 6-8% conversion losses of converting DC to AC electricity.
- **Using second-hand PV panels.** Functional second-hand PV panels are available for about 40-50% of prices for comparable factory-new modules, and often even for free because PV modules are becoming a waste problem. The costs of electricity production can be reduced accordingly.
- **Zero-cost air conditioning.** The cold air or water produced by the heat pumps can be used for air conditioning, in combination with small (~2000 l) tanks of cold water as thermal mass buffers. Since air conditioning needs are only present when there is sunlight, and a heat pump for charging a STES store is basically an oversized air conditioner, no additional energy for air

conditioning will be needed. If energy needs for heating and air conditioning would be the same, this halves the energy needed for them.

- **Saving on pumping energy.** Heat pumps need water pumps to charge the heat storage, but no water pumps to move energy from solar thermal collectors to a location close to the heat storage. Instead, electric transmission from PV panels us used, which has lower transmission losses compared to pumping against fluid friction.
- **Cheaper installation costs.** Installing PV panels is simpler and thus cheaper than installing thermal solar collectors, which requires a lot of insulated pipework, more heavy-duty anchoring to the room structure etc..

Additional side benefits. The concept presented here has other benefits over thermal solar panels that do not have an immediate financial impact:

- **Electricity is more flexible.** Electricity can be used for many more purposes compared to heat, making this solution more agile and flexible than thermal solar collectors. The system is basically a severely oversized PV plant, which will be able to cover the house's electricity needs even throughout winter. It will also provide the energy for heating, but this is a less urgent need, buffered by several months of heat storage.
- **Suitable for all-electric energy grids.** The PV-based system proposed here fits well into the "all-electric" strategy that many countries pursue for their transition to renewable energy. It can for example provide spare generation capacity for the grid, which the grid can use to deal with peak loads.
- **Avoiding grid transmission losses.** Since all solar energy is consumed locally, this avoids the 5-8% conversion and distribution losses of the electric grid. This is not true for the alternative of selling PV electricity in summer and purchasing grid electricity in winter to run a ground-source heat pump.
- **Avoiding peak loads on the grid.** Compared to running heat pumps directly from grid electricity in winter, this system avoids peak loads on the grid on cold winter days when everyone would want to run their heat pumps. Likewise, due to all-local electricity production and the cold water tanks, the system also avoids any peak loads (any load, in fact) on the grid for air conditioning in summer.

- **Additional heat available without additional equipment.** The Drake Landing Solar Community uses gas burners to post-heat water on cold winter days where the energy storage could not provide the necessary heat. A fossil-fuel free alternative is to run heat pumps with grid electricity in that case. With the system design proposed here, these heat pumps are already available, as they are used in summer to charge the heat storage. Also, some PV electricity is available even in winter, and by converting it with heat pumps to heat and storing it in hot-water tanks for short-term use, most of the additional heat requirements on winter days will not need grid electricity at all.
- **A seasonal storage for photovoltaic electricity.** Compared to running ground-source heat pumps in winter, this system basically provides a very large, seasonal accumulator for solar electricity. It is stored in summer when it is available in excess and used in winter. Similarly, day-to-day volatility of solar PV production in winter is also equalized via heat pumps and short-term heat storage. This is a major part of solving the volatility issue of renewable energy, here be storing it as usable heat and not as electricity.
- **Alleviating the urban heat island effect.** Thermal solar panels of ~34% module efficiency are basically black surfaces that convert all sunlight to heat and route 34% underground while 66% heats the air, contributing to the urban heat island effect. In contrast, PV modules with 21% module efficiency coupled with a COP 4.5 heat pump will, on the net, route 21% * 4.5 = 94.5% of the solar energy hitting the collector area underground. This way, it helps to alleviate the urban heat island effect, as this is equivalent to a cool roof with 94.5% reflectivity. When this technology is deployed on a large scale, this should become noticeable.
- **Much higher collector efficiency.** Thermal solar collectors have a module efficiency of ~34% (the DLSC example) while modern monocrystalline PV modules achieve “only” 22.8% (source) – we assume 21% here for readily available modules. Heat pumps boost the PV module efficiency: to exceed a thermal solar efficiency of 34%, a heat pump would only need a coefficient of performance larger than 34% / 21% = 1.62. This is easily achievable. Using 25 °C indoor air as the source and 60 °C water as the output, the temperature difference is 35 °C, just as in the European standard test conditions for heat pumps. Under these conditions, heat pumps achieve a COP up to 4.5 (source),

nearly tripling (!) the effective collector efficiency compared to thermal solar collectors (note :speech_balloon:).

- With a COP of 4.5, the PV / heat pump combination makes for an effective thermal module efficiency of 21% * 4.5 = 94.5%. Well irradiated outdoor space is often the limiting factor in cities, so being able to install 94.5% / 34% = 2.8 times more solar heating capacity than with thermal solar panels is a major improvement.
- **Better cold-weather performance.** Due to their limited thermal insulation, flat-panel thermal solar collectors have a bad efficiency in cold weather. Evacuated tube collectors perform much better here, but are also much more expensive and need more surface area for the same nominal (summertime) heat output. Evacuated flat plate collectors combine the best of both worlds, but are also expensive and not yet readily available on the market.
- In contrast to that, photovoltaic modules have a *higher* efficiency in cold weather due to lower silicon temperatures. PV modules will easily be the most efficient collector in wintertime, as even evacuated flat panels will not achieve their 94.5% effective performance (as calculated above) in full sun. In overcast sky conditions, the advantage will be even higher because thermal collectors would not achieve the minimum temperature for space heating (30 °C) and thus have 0% effective performance, while PV panels with enough surface area can still power at least one heat pump. So to achieve a high direct solar contribution to heating in wintertime, this is clearly the best choice.

Water tanks as possible main storage. Water tanks are an established option for small seasonal thermal energy storage plants (see). They require less pumping energy to charge and discharge, providing an even higher COP. Also, they make the heat faster accessible, while ground based storage needs water tanks as buffers because heat cannot be extracted as fast. However, they require space, which will not always be available in city buildings; and beyond a certain capacity the total costs of a tank system become larger than that of borehole thermal energy storage.

Now when applying the heat-saving techniques from this document first (heated clothing, small heated spaces etc.), a building's heating requirements will already be 75%-90% lower. At that level, seasonal thermal energy storage with *only* water tanks could become the best option, both financially and space-wise.

Back-of-the-envelope calculation: water tank for a 20-person household. Seasonal thermal storage is more efficient the larger it is, as the lower surface-to-volume ratio prevents excessive heat loss. So let's estimate the necessary size of a hot water tank for a 20 person household such as the future Reef:

1. **EU-28 heat needs per person.** Space heating plus water heating in all households in EU-28 Europe in 2017 was 7 635 790 TJ + 1 762 499 TJ = 9.398289 EJ (source, via)

   Europe had ca. 511 million people in 2017 (source). This means 5109 kWh/(person * year) (calculation). Since this is an average for all of Europe, it will apply pretty well to the heat needs in a central European location.

2. **Stored heat needs per person.** The example from DLSC shows that direct solar irradiation can be used to cover about half of household heat consumption over the course of a year, so the storage should be for about 60% of the year's total heat requirements: 5109 kWh/(person * year) * 0.6 = 3065 kWh/(person * year)

3. **Tank volume per person.** Water has a heat capacity of 4180 J/(kg*K) and the usable temperature difference is at most 65 K (30 °C floor heating water to 95 °C initial storage temperature). So to store 3065 kWh/person for the heating season, this would require 37.7 m³ of water per person (source).

4. **Applying efficiency.** Assuming that 80% of heating needs can be saved with energy conservation measures including other techniques from this document, this is reduced to 37.7 m³ * 0.2 = 7.54 m³ to store 3065 kWh/person * 0.2 = 613 kWh/person.

5. **Storage sizing for 20 people.** For a 20-person community household, this results in a total required storage volume of 7.54 m³ * 20 = 151 m³ to store 613 kWh * 20 = 12 260 kWh.

6. **Tank measures.** An interesting architectural option is a used stainless steel storage tank from the chemical industry placed centrally in a building. Structurally it would rest on the ground and be insulated all around to prevent excessive heat losses. Heat leaks in summer would be offset by the heat pumps providing cooling, and in winter they would contribute to space heating, improving the charge / discharge efficiency. In a four-storey building with an undivided upper storey and 2.30 m "economical" storey height, 6 m tank height

plus insulation should fit into three storeys (confirmed below, as 40 cm insulation is needed). Assuming a simple cylindrical form, a 151 m^3 tank of 6 m height will then be 5.66 m in diameter (source).

7. **Insulation thickness.** 20% seems a good guess for base load heating that never has to be turned down during the heating season. In other words, 20% natural heat loss through the insulation during the heating season is acceptable, which amounts to 12 260 kWh * 0.2 = 2452 kWh. We have a 6 month = 180 day heating season and 157 m^2 tank surface. This allows an average heat flow of 2452 kWh / (180 d * 24 h/d * 157 m^2) = 3.62 W/m^2. With a (95 °C + 30 °C) / 2 = 62.5 °C average tank temperature, the temperature difference to a 14.5 °C indoor temperature is 62.5 °C - 14.5 °C = 48 °C. Styrofoam insulation has a thermal resistance of 0.03 W/(m*K). To limit heat flow to 3.62 W/m^2, it would have to be 40 cm strong (formula, calculation).

8. **Lost floor area.** A tank of 5.66 m + 2 * 40 cm = 6.46 m diameter means that a floor area of pi * (6.46 m / 2)^2 = 32.8 m^2 is lost per storey, or 3 * 32.8 m^2 = 98.3 m^2 over the tanks three-storey height. Assuming a “compact but reasonable” 25 m^2 per person (between a 13 m^3 legal minimum and the current 42.5 m^2 EU-28 average), a 20 people household would have 500 m^2 net, or 500 m^2 + 98.3 m^2 = ~600m^2 gross floor area including the water tank. So 16.4% of floor area is lost to the water tank, which is considerable but doable.

9. **Necessary PV area.** To collect the tank’s total 12 260 kWh stored usable heat with a system efficiency (incl. charging pumps) of 21% * COP 3.5 = 73.5% in 6 months non-heating season in May to October in Munich (where 65.4% of the total PV production occurs, of a total of 947 kWh / kWp – source), the required collector area is just about 27 m^2 (calculation).

6.8 Heating with compost

Composting produces low-grade heat, but in both household and industrial composting, this heat is not used for anything. It can however be used to heat a whole house, as shown below. For a good overview of all published material about compost heat extraction, see: “Heat Recovery from composting: A Comprehensive Review of System Design, Recovery Rate, and Utilization”.

The compost produced from kitchen scraps of urban inhabitants will not be enough to provide all the heat required for space heating, but collecting organic trash for free around the neighborhood is easily possible. Heat extraction from composting is similar to partially burning the biomass. Usually, the amount of heat recoverable depends heavily on the scale on the system:

> On an energy-per-weight basis, energy recovery rates were 1159 kJ/kg DM [dry mass] (s = 602 kJ/kg DM) for lab-scale systems, 4302 kJ/kg DM (s = 2003 kJ/kg) for pilot-scale systems, and 7084 kJ/kg DM (s = 3272 kJ/kg DM) for commercial-scale systems. (source, p. 11)

This is due to much lower surface-to-volume ratios in large-scale systems, avoiding heat loss to the environment. In the system below, all heat loss to the environment contributes to space heating because the compost heat is placed inside the house, so we can assume the 7084 kJ/kg dry mass heating value of compost. In a highly energy efficient community of 20 people, a total of 12 260 kWh is required for space heating. This would be contained in 12 260 kWh / 7084 kJ/kg = 6230 kg of compostable biomass on a dry mass basis, resulting in 6-10 m^3 of humus produced per year. The compost vessel size should be large enough to store as much finished humus as can be loaded on a typical tipper truck or trailer for transportation to farms.

There are several advantages over burning biomass: (1) no need for drying the biomass before burning; (2) all biomass can be composted, whereas biomass burners are always specialized for one sort of fuel only; (3) there is no particulate air pollution in contrast to burning wood, and this is an important point in cities; (4) the end product is humus, a valuable agricultural input, and its accumulation in soil is a way of carbon sequestration. In contrast, the complete burning of biomass is at best carbon neutral.

In addition, there are advantages over the current practice of municipal collection of organic trash and centralized composting: (1) the heat is used for space heating instead of being lost; (2) the humus end product is significantly lighter and more compact than the initial biomass (incl. branches, leaves etc.), which should make its transportation to farms about 3 times more energy efficient (a guesstimate, so far); (3) the neighborhood-scale collection can be done manually because the weight, volume and distances are small, and this decarbonizes this part of the collection logistics.

An initial proposal for a system would be to place a 2-2.5 m diameter stainless steel tank vertically into the center of the house, containing the composting biomass. The tank can for example be obtained second hand as a 20 ft tank container. The biomass would be filled in at the top and extracted after 2-3 years at the bottom. Different from all systems outside of buildings, here 100% of the composting heat will eventually be used for space heating as it seeps through the walls into the building. The tank would be insulated enough to prevent excessive heat loss or heating up the surrounding rooms too much, and if necessary a heat exchange loop of copper tube might be routed between the tank and insulation and route captured heat into a hot-water tank for distribution to other parts of the building. Some other equipment will also be necessary: forced ventilation with compressed air from below; a heat exchanger in the hot steamy compost fumes; and an extraction screw, ideally pouring the compost right on a truck parked aside the building.

6.9 Wastewater heat recovery

Heat from all wastewater should be extracted using passive cooling and, in a second stage, an electrical heat pump, before finally discharging the wastewater. There will be an optimum temperature for discharging the wastewater, namely the temperature where heat can be just as efficiently extracted with the heat pump from outdoor air or (better) the ground. Ground temperature is ca. 12 °C year-round, so that would be the temperature to discharge wastewater at. Or probably a bit lower (9-10 °C) as heat extracting from water at surface level does not need as much pumping energy as extracting it from a 30-80 m deep borehole. The average wastewater temperature can be determined based on hot and cold water volumes in a household, and from that the recoverable energy can be determined.

Several engineering and DIY approaches for greywater heat recovery exist:

- “Greywater Heat Exchanger in A Barrel Progress”
- “Design and Analysis of a Residential Greywater Heat Recovery System”

7 Cooling

7.1 Wearable air conditioning

Wearable air conditioning devices are slowly appearing on the market, and there are good reasons for this technology:

> "The thought process was and is that if you increase the set point of your thermostat to something slightly warmer than comfortable, and then use this for supplemental cooling, there will be a huge energy savings [...] The company claims that, because [...] [the device] would allow people to cool themselves rather than their entire office or home, it could translate to energy savings of between 15% and 35% of a building's overall cooling costs."
>
> (source: "The billion-dollar race to invent a wearable air conditioner")

However, devices for use inside buildings can be different: cheaper and more efficient because they do not have to rely on battery power. here is a proposal: a 4 - 5 l insulated water bladder with very cold water (-10 °C by using salt water) and a heat exchanger with a small battery operated pump that circulates 20 °C water through the clothing. One would wear light, long, insulating clothing, for example down clothing. When the heat buffer is exhausted after 1-4 hours (depending on inside temperature), one would go to a recharge station an plug in a hose. The warm water will then be sucked out of the water bladder, and new cold water will be filled in. This will happen within 10-20 seconds, so it is not uncomfortable at all. The recharge station can be built from a normal deep freezer by creating a hole with hose connector in the door and adding a two-way pump to that. There would be one large liquid tank of about 100 l in the freezer, and water will be pumped in and out of that same tank. This way, only one hose and one tank vessel is needed. The freezer can still be use for food storage outside of summertime.

7.2 Small cooled spaces

Similar to small heated spaces, but to replace air conditioning rather than heating. There is absolutely no reason to air condition a whole house. Ideas for small cooled spaces:

- **Cooled bed.** The blanket would include a silicone hose with circulating cold water at the bottom. The blanket would be heavily insulated, to keep the heat out.

7.3 Thermal mass air conditioning

A simple and energy efficient way of keeping the inside of urban houses cool during the day is using water as a thermal mass for buffering the heat, dissipating it during the night again. Water is amazing because it has a specific heat capacity at STP of 4.18 J/(g K). Compare that with 0.74 J/(g K) for concrete or 0.39 J/(g K) for wood (and probably the average for interior objects of a house). So a relatively small amount of water can increase the thermal buffer of a house considerably.

Where this is not sufficient, heat pumps can be used as a supporting measure: 25 °C warm water as a heat sink still allows a heat pump to operate more efficiently than 40 °C outside air (see). This system is the same technique as used for seasonal thermal energy storage, just applied to cooling. It needs a different reservoir (water or ground boreholes) though as the goal is different.

There is no need for seasonal storage here, though. Instead, the water will simply be cooled down during the night again, perhaps with enough buffer for up to warm nights where cooling is difficult. A highly efficient way of cooling is to let the water run down inclined rooftops in a circular pumped loop system, providing radiative cooling to the night sky, plus some evaporative cooling. This can be enhanced by covering the roof with polymers that have a high emissivity in the athmospheric IR radiation window. Luckily, such polymers area available commercially as film material from 3M, as used in this study. There is no need to apply a silver coating as done in that study, as the cooling will be only done during the night. However, applying that cooling provides a “supercool” roof during daytime, cooling to sub-ambient temperatures by itself even under direct sunlight.

Practically, one could just use water in containers inside the house or in a cistern next to the house instead of active air conditioning. As long as the air temperature during the night is comfortable and the amount of water is sufficient, there will be no need for air conditioning. The only energy needed is for a fan to move the heat in and out of the water, and to distribute the cold air in the house. This can also be used to retrofit existing houses, even rented flats. Simply place lots of 20 l water cans in the flat, but distributed so that the floor is not strained too much. And then use a fan running during the night to cool down the room and the water in it as much as possible again.

7.4 Cool and supercool roofs and walls

Surfaces that both reflect incoming sunlight and also cool by emitting IR radiation, preferably in the atmospheric window, keep relatively cool under direct sunlight and can even cool to subambient temperatures (see: overview of recent research). One of the most promising materials for mass production is just a commercial dual-polymer film material coated with silver sputtering on its back (source).

Applying existing paints and materials and also the new materials in architecture can provide better energy efficiency and comfort in summer:

> Cool roofing limits total cooling loads in summer, reduces the severity of the urban heat island (UHI) problem in towns and cities, and helps eliminate peak power demand problems from operation of many air conditioners. Added feedback benefits from cool roofs [...] include ventilation with cooler air and higher performance of adjacent chillers when in cooler air. (source)

7.5 Reverse chimney effect cooling

This is a largely unknown principle for passive cooling of buildings, observed and developed by Buckminster Fuller with his geodesic domes. Air is drawn into the top of a dome and exits through side vents at the bottom, driven by convection of air heated by the sun. The air drawn in cools down for some poorly understood reason (Venturi effect, or conservation of energy; see carburetor icing). For the best compilation of sources about this phenomenon, see: “Buckminster Fuller’s Chilling Domes: the physics”.

This technique could be used in urban architecture, either for the main house, or for a naturally cool space in the garden or on the rooftop.

8 Electricity

8.1 Flexible electricity demand

Even before this is used as a feature in the national grid, you can "help the grid" by consuming electricity only when renewable energy production is high and demand is low. If everyone does this, it avoids the need for most energy storage, currently the biggest challenge of integrating renewable energy into the grid.

Examples include:

- Cook with electricity when renewables production is high, otherwise cook with biogas and hydrogen. This also applies to the water kettle – instead of an electric kettle, develop and use a dedicated gas-powered water kettle.
- Use a circuit that starts the washing machine and dishwasher when a delay, triggered when renewables production is high.
- Have enough clean clothing so that using the washing machine only becomes necessary every 2-4 weeks. That should be enough buffer to catch times of high renewables production. You basically store energy in clean clothes.
- Use fridges and deep freezers with cold storage and an extreme amount of insulation. Such devices are already made for campervans. They store energy non-electrically in cold and can stay off for 12 hours or more while renewables production is low.

8.2 Low-voltage DC installation

Disadvantages of current grid-tied PV. Currently, nearly all houses with a photovoltaics (PV) plant convert low-voltage DC from the PV panels to 230 V AC via grid-tied inverters, and then partially consume that electricity internally while feeding the rest into the grid. Compared to a low-voltage DC system, this makes PV energy more expensive because (1) working with 230 V AC electricity is potentially unsafe so most people will not do much of that in a DIY manner, (2) at least some work with grid electricity is usually reserved for "certified professionals" who will regularly demand payment for their work, (3) the inverter itself costs money and is often the first device to fail in a PV installation while PV panels have an estimated lifetime of 25 years, (4) the inverter also incurs conversion losses, (5) many modern electrical consumers like electronics and LED lighting are internally DC devices, so there are additional conversion losses for converting AC electricity back to DC.

Compared to that, a DC electricity PV setup that is not tied to the grid makes a lot of sense. By following the SELV standard for its construction, there is no danger of electrocution at all, making DIY work on this system safe. Ideally it will use no or very little battery storage because batteries degrade over time and make electricity more expensive and less ecologically sustainable (though also compare section “Free battery storage”). Instead, as much of the locally produced electricity would be used up immediately by doing useful work that is somewhat flexible in time (see section “Storing solar energy in useful work”).

Two wiring systems. In effect, a house would then have two electrical systems: the normal 230 V AC grid for high-power devices and the SELV DC system for low-power DC devices. The DC system should probably use 24 V DC because that has lower line losses than 12 V DC and is still a voltage where devices are commercially available easily because trucks use 24 V DC. While the house does not produce power for the DC system, a AC-DC converter will provide that from the grid.

Self-consumption with AC devices. There is also a way to use locally produced PV electricity for AC consumers, with automatic switchover to the grid when not enough locally produced electricity is available. For that, see “A much better solution for solar self-consumption”. This works with a much simpler and cheaper type of inverter that is not applicable for grid-tied operation, but is primarily a cost-optimization strategy than an ecological intervention. It is however a solution that makes PV electricity attractive in areas where feed-in to the grid is forbidden.

8.3 Storing solar energy in useful work

In urban areas, the only renewable energy sources that are readily accessible are ground heat and air heat (via heat pumps) and solar irradiation (via thermal or photovoltaics collectors and via photosynthesis). So of course, everything would be covered with photovoltaics cells to capture as much electricity from winter sunlight as possible. Wind energy is not accessible in significant amounts (low height, only vertical wind turbines possible etc.). Using ground heat and air heat requires electricity or mechanical movement to run heat pumps, so is basically just a way to amplify / leverage that energy. And that energy must come from the sun, the only other renewable energy source. So the principle of an energy self-sufficient building in the higher latitudes (with pronounced seasons) must be to store solar energy in various ways during the summer for use in winter.

Since batteries are expensive storage technology, they are not practical for seasonal energy storage. For this reason, an array of other technologies would have to be developed to store solar energy in a form closer to its usage. For example, energy can be stored as:

- **Heat for cooking.** Since cooking is the largest use of energy in a typical summer day in a house, it is the best candidate for using up excess photovoltaics electricity. This would be done by buffering the energy as heat, to prevent the cost and complexity of battery storage. In practice, excess PV energy would be used in DC form to heat up fireclay blocks with embedded nicro wire spirals, up to about 900 °C. The fireclay stones would be stored in a compact insulated container vertically below the kitchen stove. To extract the heat for cooking, cold air will be blown into air gaps in this block of fireclay, and the emerging hot air will be routed through insulated tubes to the kitchen stove's pots. As the air temperature decreases, the system will increase the air volume to compensate. When that method reaches its limit, a gas flame will be burned inside of this air to heat it up further. Preferably, biogas would be used for this. Cooking with gas that is burning in hot air will still save fuel compared to a normal gas stove.
- **Drying capacity.** Basically, by drying calcium chloride to its anhydrous form when energy is available in excess.
- **Cooling capacity.** Zeolites, as used in self-chilling beer kegs, can be used as non-electrical energy storage for a fridge.
- **Clean clothing.** With enough clothing, it is easily possible to wash and dry the clothing only in summer where excess photovoltaics power is available and where outdoor drying is easily possible.
- **Seasonal heat.** See the section about seasonal heat storage.
- **Cooking fuel.** Drying organic trash for use in an anaerobic digestion plant on demand, then cooking with that biogas.

- **Heating fuel.** Wood and other burnable biomass is basically stored solar energy. Its energy content can be raised considerably by drying it, which is a good use of excess solar energy.
- **Fuel for generating electricity.** Hydrogen in low-pressure storage vessels; dried organic trash for use in an anaerobic digestion plant, producing biogas; both used in internal combustion engines of the linear alternator type.

8.4 Free battery storage

In a renewables-powered future, there can never be enough storage for electricity. Here is a way how a small group of people can create a major amount of battery storage for basically free, and even derive financial benefit from it. The benefit comes from the fact that locally produced renewable electricity from free salvaged battery cells is three times cheaper than selling the electricity to the grid and buying it back when needing it later (Germany, 2019). It also is a pioneering effort for the time when grids will buy electricity from distributed storage like electric vehicles at higher prices than they buy renewable electricity at the time of production now.

Here is how to make this happen: In 2015, about 2.4 billion 18650 cells were produced, of which 1.8 billion were used in consumer devices etc. and 600 million by Tesla. These 1.8 billion are a stable yearly demand since 2010 (source). Given the typical lifetime of these cells of less than 5 years (300-500 cycles in consumer devices), this means they are replaced, not added. As these cells are not recycled, 1.8 billion cells are available every year for free. With a remaining average capacity of (say) 2 Wh (~20%) per cell, that means 3.6 billion Wh = 3600 MWh = 3.6 million kWh of storage capacity can be added every year. In 10 kWh units per household, this is enough for 360,000 “free” household-sized backup power plants per year.

These backup plants would be built as follows:

There would be a fireproof charging and discharging station where enough cells can be charged and discharged at a time to cover 80% of the households electricity needs. High demands (“cooking at night with electricity”) will be excluded and covered form the grid instead. By being fireproof and ejecting burning battery cells into a fireproof chamber, even “unsafe” undervoltage lithium-ion cells can be re-used safely.

In addition to the charging and discharging station, there would be large storage boxes where the batteries are stored in bulk. Each cell would be protected with a plastic casing so that the cell holders in the charging / discharging station can reach the terminals but so that the cells in loose bulk can never create a short circuit, because short-circuiting unprotected lithium-ion cells can lead to fires.

A mechatronic system would then be able to remove cells from the charging / discharging station and replace them with other cells. A proposal would be a large wall of battery cells, facing with their negative terminals to a cartesian robot that can extract and insert them one by one. The movement to insert a cell would consists of pushing it in, rotating it by 30° to lock a bayonet style lock, and releasing it, which results in spring pressure on the positive terminal securing the bayonet lock. The bayonet locking points would also serve as the negative terminal, which is possible by removing some of the plastic insulation from the cell’s metal container. Because the whole container is the cell’s negative terminal, with the exception of the one end serving as the positive terminal.

That way, electricity can be stored in pallet sized boxes. A 1 m^3 pallet with loose bulk 18650 cells at 25% cell volume to total volume ratio and 2 Wh remaining capacity per cell could store roughly 30 kWh of electrical energy, enough for 4 complete days in an optimized communal household with 20 people.

There is no good reason to make an urban household off-grid, so there is no minimum required amount of battery storage. Every amount provides additional financial benefit, so the commune would simply collect and prepare as many battery cells as they can find.

Preparing the battery cells just means breaking open the batteries of notebooks, cordless powertools, electric bicycles and the like, harvesting the cells and placing them individually into protective plastic containers that also have a barcode on their side. The mechatronic system uses this barcode to automatically register the cell and then stores all relevant information about it: testing results, current carrying capacity, current charge state, performance degradation over time and finally that the cell died and has been removed from the system. This also allows to store cells with mixed charge states, mixed capacities and mixed current carrying capacity in the same container, as the charging / discharging station can identify and treat each cell individually.

A similar system can be created for the rather arbitrarily shaped lithium-polymer battery cells from smartphones, notebook computers etc.. They would be placed into standard sized protective containers which then allow loose bulk storage and handling with an automated mechatronic system.

8.5 Photovoltaic modules as wall covering

To make an old (or even new) facade weatherproof, used photovoltaic modules are an attractive option. It's weatherproofing for decades without deterioration, also generates some power, and these modules are available for 0.25 EUR/W_p used, which equates to 30% of the new price. For the permanently shaded portions of walls, it makes sense to use broken PV panels (as long as the glass is undamaged) as this provides a visually consistent and equally weatherproof wall surface.

9 Water

9.1 Drinking tap water

It would be interesting to calculate the emission savings when drinking only tap water based beverages, compared to other options (milk, fruit juices, bottled water). Savings will come from transportation fuel savings (which are considerable as beverages are heavy), reduction of dairy agriculture (which saves methane emissions etc.), savings from glass and plastic bottle manufacturing. Transportation through the public water pipeline is just so much more energy efficient. Also, if really desired, fruit juices should be purchased as concentrate and mixed into juices at home.

9.2 Water efficient hygiene

A lot about hygiene is not a public health issue but a psychological issue. Human psychological issues are not a proper reason to destroy the environment, so it’s time to rethink hygiene.

- **Private bathrooms.** Bathroom hygiene is mostly a psychological issue – a communal bathroom has to look and smell clean as dirt and smells are a biologically ingrained cue for pathogens. However, not all dirt contains pathogens. A way to decrease the actual and perceived need for bathroom hygiene is to give everyone a private bathroom – one simply cannot infect oneself with own germs as one will either be infected or immune already. In addition, private bathrooms are the simplest way to prevent transmission of (gastrointestinal) diseases. Everyone would also clean their own bathroom, of course, removing the typical friction around this topic in communal living setups.
- **How to shower less often.** Everyone tells people to "take shorter showers" in order to reduce their GHG emissions, but nobody dares to say: you don't need to shower that often. That's a cultural taboo, and we can't afford taboos anymore because this is a global ecological crisis. For example, telework is a way to avoid excessive need for showering.
- **Recirculating showers.**
- **Composting dry toilets.**

9.3 Rainwater capture and infiltration

Relevant literature:

- **To Catch the Rain.** About rainwater harvesting. The book is open content but you need to enter your email address to get it.
- **Prospects for Managed Underground Storage of Recoverable Water.** 2008. 350 pages. Very interesting discussion of how to store excess water in groundwater, by infiltration with basins, trenches and wells. Quite high-level and not containing instructions directly, but instructions can be derived from this after study.

9.4 Wastewater evaporation

Runoff water and even lightly contaminated greywater is usually not suitable for groundwater infiltration, and infiltration of pure rainwater also makes no sense if your city has extensive systems in place to drain groundwater away as fast as possible.

In these cases, evaporating that water is another meaningful way to use. Water vapor carries away a lot of sensible heat, so if applied in a whole neighborhood, evaporating large amounts of collected water during the summer will probably reduce outdoor temperatures. Just take care to not install any dark surfaces in order to support water evaporation – if the intention is cooling, this is self-defeating as it only contributes to the urban heat island effect.

As a side benefit, evaporating the resulting greywater allows you to legally use collected rainwater for free, that is, without having to pay wastewater fees for it. When applied on a large scale and in tandem with careful water conservation, wastewater grading and filtration at the point of consumption, it should even be possible to avoid 90-95% of wastewater making it to the sewage system at all. This is not a major challenge in European cities, but in developing cities it may be a way to deal with the overchallenged or non-existing sewage system. A public sewage system might not be needed at all, as the remaining wastewater can be collected with pumping vehicles.

10 Transportation

10.1 Public transport hacks

Foam pads for comfort and warmth. Until public transport starts offering extra cushions for the knees of very tall people, or the backs of somewhat delicate riders - just bring your own. It does not have to be an overpriced outdoor pillow. A folded piece of down-cycled yoga mat, or sleeping pad will do fine. Store it directly against your back in a rucksack for improved carrying comfort, or better protect a notebook's bottom edge, with minimal weight or volume issues. Now you can also work far more comfortably at that coffee place or in the park and pick your favorite place without getting cold too quick. As another side effect, this kind of clothing system might find its first entry into the market as outdoor clothing for professionals working in cold weather regularly.

10.2 Safe and comfortable bicycling

The bicycle is one of the most efficient means of transportation known to mankind, but its adoption is far beyond potential in urban centers due to cultural and psychological biases related to comfort and safety. Making bicycling in cities both safe and comfortable is partially a political problem, but until that gets covered, there is a lot that individuals and groups can do as well:

- Automatic door closers should be adjusted for bikes and kids.
- Shared bike locks (Bluetooth codes) - share with friends, social cohesion
- E-bikes and commutes (event week / month + incentives to curb apparent extremism), e-scooters charging and energy awareness Better practices and less prejudice concerning remote work

10.3 Electric velomobiles

This is ultimate in personal low-cost mobility. A bicycle is comfortable to use within about 30 km (or two hours one way, whichever is lower) of a home location, and uncomfortable beyond that, esp. due to the seating position, missing protection from rain etc.. A velomobile with permanent or retractable enclosure, four wheels, space for baggage and a strong battery and motor however would allow multi-day tours of 1000 km and beyond. This allows the commune to have sustainable DIY mobility, without having to earn and pay money for bus tickets etc..

In contract to a normal bicycle which is optimized for low cost, simplicity and durability, this velomobile would be optimized for comfortable and sustainable traveling. This is also a complex and relatively expensive devices, so a commune would only have about two, each for one person plus baggage. One is not enough, as on longer tours there should be two for mutual support / redundancy. Also, people often like to travel together.

Ideas for design and construction:

- Both two-wheel and four-wheel velomobiles have their advantages. In any case, the velomobile must be narrow enough to use a single-track foot trail, as that allows a lot of backcountry use, and to avoid using streets with motorized vehicles (as these are quite dangerous). Probably, 60 cm left to right wheel distance is the maximum for single-track usage.
- For use in the wider local area, combining the velomobile with a self-developed battery swapping standard is a good way to lower the weight and increase the average speed. Finding locations for the battery swap stations is simple: offer private households to set up a small photovoltaics installation that lowers their electricity bill if they agree that a portion (as much as needed) of the electricity is used to charge the batteries, and that people with the velomobile can come and swap batteries at any time (by accessing a locked box where the battery is charging).
- The velomobile would be able to drive without pedaling, but the speed will be limited to 30-35 km/h to limit air resistance (which increases quadratically) but also for safety reasons.
- When using a two-wheeled velomobile, a shape like the BMW C1 motorcycle would be both comfortable and protecting. There would be pedals, but unlike in a bicycle one would sit on a flat, cushioned surface. Also one would be able to choose to pedal (towards the front) or not (resting the feet away from the pedals, like with a motorscooter).
- For long-distance use, the velomobile should have a trailer of photovoltaics panels. It would be able to telescope in length while driving on an empty road, to extend the catchment area. And one of the best ways to harvest energy will

be to rest for 2-4 hours at noon, letting the sun fill the batteries. Cycling at noon in direct sun is not much fun anyway.

10.4 Hospitality

Intra-city hospitality networks. These networks would allow to stay over at or near a place one visited in a different part of the city. Unlike AirBnB and similar, this system would work without monetary compensation – instead, it is in exchange for hosting other people at ones own place.

Benefits include:

- Not having to use GHG-inefficient transport modes, which are often the only ones available late at night: cabs and night buses.
- Time savings when one has to visit the same place or a place in the same part of the city again the next day.
- Extending the capacity of a communal home for guests by temporarily moving out for a few days.

Resource-efficient hosting. The current hospitality industry is certainly not the most climate-friendly way to accommodate temporary inhabitants of a city. Rather, hosting friends etc. in a multi-use space inside ones own house will be much more efficient.