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Budovy v kontextu klimatických cílů

Buildings in the Context of Climatic Goals

Habilitační práce

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Abstrakt

Práce se zabývá problematikou možnosti mitigace změny klimatu pomocí snižování produkce skleníkových plynů v budovách. V první části práce je shrnut současný stav poznání. Následuje analýza fondu budov ČR z hlediska přispívání jeho provozu k produkci skleníkových plynů a vyjádření potenciálu ke snížení této produkce prostřednictvím zvyšování energetické účinnosti budov a využíváním obnovitelných zdrojů energie v budovách. Poslední část práce se zabývá problematikou stanovení referenčních hladin produkce emisí skleníkových plynů pro budovy a je doprovozena případovou studií prezentující aplikaci těchto referenčních hladin na bytový dům v ČR.

Klíčová slova

Budovy, změna klimatu, energetická účinnost, fond budov, rekonstrukce, scénáře

Abstract

The thesis deals with the issue of mitigating climate change by reducing greenhouse gas production in buildings. The first part of the thesis summarises the current state of knowledge. This is followed by an analysis of the building stock of the Czech Republic in terms of the contribution of its operation to the production of greenhouse gases and an expression of the potential to reduce this production through increasing the energy efficiency of buildings and the use of renewable energy sources in buildings. The last part of the thesis deals with the issue of establishing reference levels of greenhouse gas emissions for buildings and is accompanied by a case study presenting the application of these reference levels to an apartment building in the Czech Republic.

Keywords

Buildings, climate change, energy efficiency, building stock, renovation, scenarios

Prohlášení

Prohlašuji, že jsem tuto habilitační práci s názvem „Budovy v kontextu klimatických cílů“ vypracoval samostatně. Dále prohlašuji, že veškeré podklady, ze kterých jsem čerpal, jsou uvedeny v seznamu použité literatury.

V Praze dne 25.11.2021

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podpis autora

Poděkování

Především děkuji své rodině za to, že mě dlouhodobě podporuje v mé odborné činnosti. Speciální dík patří mé ženě Peťule, která statečně snáší mé intenzivní pracovní nasazení, je bezvadnou mámou našich dětí a dlouhodobě táhne provoz naší domácnosti. Bez její obětavosti a tolerance bych tyto řádky nemohl psát. Oběma našim rodičům vděčíme za jejich neutuchající podporu.

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Díky!

Obsah

Použité symboly a zkratky

Zkratka	**Výklad**
BIPV	Fotovoltaika integrovaná v budovách (z angl. building-integrated photovoltaics)
°C	Stupeň Celsia
CCS	Zachycování a ukládání oxidu uhličitého, z angl. carbon capture and storage
CO_2	Oxid uhličitý
$CO_{2,ekv.}$	Ekvivalent oxidu uhličitého
COP	Konference smluvních stran UNFCCC, z angl. názvu Conference of Parties
ČHMÚ	Český hydrometeorologický ústav
EEA	Evropská agentura pro životní prostředí (z angl. European Environment Agency)
EGR	Emissions Gap Report, zpráva pravidelně vydávaná UNEP
EU	Evropská unie
GCOS	Globální systém sledování klimatu, z angl. názvu The Global Climate Observing System
GHG	Skleníkové plyny (z angl. Greenhouse Gases)
Gt	Gigatuna
GWP	Potenciál globálního oteplování (z angl. Global Warming Potential)
HDI	Index lidského rozvoje (z angl. Human Developemnt Index)
HDP	Hrubý domácí produkt
IEA	Mezinárodní energetická agentura (z angl. International Energy Agency)
INDC	Zamýšlené vnitrostátně stanovené příspěvky, z angl. intended nationally determined contributions
IPCC	Mezivládní panel pro změny klimatu, z angl. Intergovernmental Panel on Climate Change
ISC	Mezinárodní výbor pro vědu, z angl. International Council for Science
ISO	International Organization for Standardization
IOC	Mezivládní oceánografická komise v rámci UNESCO, z angl. Intergovernmental Oceanographic Commission of UNESCO
kt	Kilotuna
LCA	Posuzování životního cyklu, z angl. life cycle assessment
LULUCF	Využívání půdy, změny ve využívání půdy a lesnictví, z angl. land use, land-use change, and forestry (používá se v souvislosti s vykazováním emisí skleníkových plynů)
m^2	Čtvereční metr
Mt	Megatuna
MŽP	Ministerstvo životního prostředí České republiky
NDC	Vnitrostátně stanovené příspěvky, z angl. nationally determined contribution
NFB	Národní fond budov
NIR	Národní inventarizační zpráva, z angl. National Inventory Report
OSN	Organizace spojených národů, angl. United Nations (UN)
RCP	Reprezentativní směry vývoje koncentrací skleníkových plynů, z angl. Representative Concentration Pathways (Moss *et al.*, 2008)
SDGs	Cíle udržitelného rozvoje OSN (z angl. Sustainable Development Goals)
ŠPB	Šance pro budovy
TZB	Technická zařízení budov

U	Součinitel prostupu tepla
UNFCCC	Rámcová úmluva OSN o změně klimatu, z angl. United Nations Framework Convention on Climate Change
UNEP	Program OSN pro životní prostředí, z angl. United Nations Environment Programme
UNESCO	Organizace OSN pro vzdělání, vědu a kulturu, z angl. United Nations Educational, Scientific and Cultural Organization
USA	Spojené státy americké
WMO	Světová meteorologická organizace, z angl. World Meteorogical Organization

1. Úvod

1.1. Popis problému

Změna klimatu je jedním z hlavních globálních problémů dneška (IPCC, 2014). Většina vědecké komunity se shodla, že je vysoká pravděpodobnost, že nástup klimatické změny z velké části souvisí s činností člověka (IPCC *et al.*, 2013), konkrétně s vypouštěním velkého množství skleníkových plynů do atmosféry. Vývoj změny klimatu tedy lze lidskou činností výrazně ovlivnit, a pokud chceme co nejméně destabilizovat současné fungování přírodních systémů a zachovat příznivé prostředí pro život, je naší povinností pokusit se negativní dopady lidské činnosti redukovat. Samozřejmě je potřeba balancovat úsilí o ochranu klimatu s ostatními potřebami společnosti a všechny potenciální dopady v souladu s principy udržitelného rozvoje důsledně vyhodnocovat (Lützkendorf *et al.*, 2012).

Mezinárodní společenství se snaží hledat cesty, jak celkovou produkci skleníkových plynů snížit (UNFCCC, 1998; United Nations, 2015; Stavins and Stove, 2016). Budovy jsou jedním z předních producentů emisí skleníkových plynů (European Commission, 2018). Na rozdíl od dalších oblastí lidské činnosti jsou již dnes známy technologie a postupy umožňující výrazné snížení produkce skleníkových plynů v celém životním cyklu budov (United Nations, 2009).

Aby bylo možné alespoň odhadnout potenciál, který budovy k úsporám nabízejí, a zvažovat, zda má smysl se zabývat jeho vytěžením, je nejprve potřeba mít alespoň hrubý odhad, jaký je současný podíl budov na produkci skleníkových plynů, jaký je přirozený potenciál pro jejich snížení a zda je tento přirozený potenciál dostačující vzhledem ke globálním cílům. Na takovýchto studiích různé vědecké týmy ve světě pracují (Musall, 2015; Bürger *et al.*, 2016, 2017), v ČR takovýto odhad zatím pro národní podmínky nebyl podrobně zpracován.

1.2. Cíl práce

Hlavním cílem práce je odhadnout, jaký potenciál ke snížení produkce emisí skleníkových plynů má český národní fond budov, a ukázat, jakým způsobem by bylo možné stanovit požadavky tak, aby jejich výstavba a fungování byly v souladu s mezinárodními klimatickými cíli.

2. Metody

Aby bylo možné přistoupit k řešení hlavního cíle práce, je potřeba nejprve definovat základní pojmy problematiky změny klimatu a sesumírovat základní fakta o dosavadním vývoji poznání o fyzikální podstatě problému, tak o lidských aktivitách v této oblasti.

Následně budou provedeny rešerše stávajícího stavu poznání s cílem shrnout aktuální odpovědi na otázky:

- Jaké jsou ekologické limity lidské činnosti s ohledem na změnu klimatu?
- Jaké jsou způsoby alokace těchto limitů z globálního měřítka na národní úroveň, potažmo na národní fond budov?
- Jaké jsou národní závazky a strategie vybraných států v oblasti změny klimatu?
- V jaké výši se odhaduje současný podíl budov na emisích skleníkových plynů?

Odpovědi na tyto otázky budou shrnuty v kapitole *3 Současný stav poznání*.

V případě, že se podaří nalézt uspokojující odpovědi na výše uvedené otázky, bude možné předpokládat, že zjištěné přístupy lze aplikovat i pro situaci ČR, a tedy bude možné najít odpovědi na tyto otázky:

- Jaký je podíl fondu budov ČR na produkci skleníkových plynů ČR?
- Jaký je přirozený potenciál fondu budov ČR pro snížení emisí skleníkových plynů?
- Je tento potenciál dostačující z pohledu celosvětových limitů?
- Pokud ne, jak by vypadaly budovy splňující stanovené limity? Jsou dosažitelné pomocí dnešního stavu techniky?
- Jaké další kroky ve vývoji a implementaci by byly třeba? Jaké je výhled budoucího vývoje v oblasti snižování produkce emisí skleníkových plynů v budovách?

Následující kapitoly stručně shrnují metody, které budou použity k zodpovězení položených otázek.

2.1. Metody zjištění současného stavu poznání

2.1.1. Definice základních pojmů

Nejdříve bude provedena definice základních pojmů, které budou používány v další práci.

2.1.2. Jaké jsou ekologické limity lidské činnosti s ohledem na změnu klimatu?

Bude provedena stručná rešerše literatury zaměřená na ekologické limity lidské činnosti s ohledem na změny klimatu. Bude vycházet primárně z podkladů v nejčerstvějších reportech Mezivládního panelu pro změnu klimatu.

2.1.3. Jak tyto limity spravedlivě distribuovat mezi státy?

Bude provedena rešerše odborné literatury s cílem najít a přehledně shrnout stávající doporučení pro distribuci klimatických závazků mezi jednotlivé národní státy. Jednotlivé přístupy budou diskutovány s cílem vybrat mechanismus, který umožní relativně spravedlivou mezinárodní distribuci klimatických závazků a poskytne základ pro další výpočty na národní úrovni.

2.1.4. Jaký je současný vývoj emisí skleníkových plynů?

Na základě dostupných statistických dat bude provedeno stručné shrnutí množství globálních, evropských a národních emisí skleníkových plynů.

2.1.5. Jaké jsou mezinárodní aktivity vedoucí k mitigaci změny klimatu?

Na základě rešerše dokumentů Ministerstva životního prostředí a dokumentů mezinárodních organizací bude proveden stručný přehled nejvýznamnějších mezinárodních aktivit.

2.1.6. Jaké jsou národní závazky a strategie vybraných států v oblasti změny klimatu?

Cílem rešerše v této oblasti je sestavení přehledu národních klimatických závazků vybraných států a navazujících strategií, pomocí nichž hodlají jednotlivé státy dosažení závazků dosáhnout. Hlavní metodou bude rešerše odborných článků a dostupných strategických dokumentů.

2.1.7. V jaké výši se odhaduje současný podíl budov na emisích skleníkových plynů?

Bude provedena rešerše literatury s cílem uvést stručný přehled o tom, jaký je podíl emisí skleníkových plynů produkovaných fondem budov celosvětově a ve státech G20. Hlavním zdrojem informací budou vědecké články a reporty organizací, které se problematikou zabývají.

2.1.8. Existují ve světě metody, kterými mohou státy přímo distribuovat klimatické limity na národní fondy budov nebo přímo na budovy?

Cílem této části bude nalézt národní metody, které umožní převod národních klimatických požadavků na národní fondy budov nebo na jednotlivé budovy. Hlavním zdrojem informací budou vědecké publikace a informace poskytnuté zahraničními kolegy.

2.2. Metody analýzy fondu budov ČR

2.2.1. Jaký je podíl fondu budov ČR na produkci skleníkových plynů ČR?

Bude provedena rešerše s cílem vyhledat data, která by mohla sloužit jako podklad pro výpočet emisí skleníkových plynů fondu budov. K výpočtu budou potřeba informace o spotřebě energie v budovách po jednotlivých energonositelích. Na základě emisních faktorů bude vypočtena roční produkce emisí skleníkových plynů z fondu budov ČR.

2.2.2. Jaký je potenciál fondu budov ČR pro snížení emisí skleníkových plynů?

Na základě dostupných podkladových studií o potenciálu úspor energie v budovách bude nahrubo vypočten potenciál fondu budov pro snížení emisí skleníkových plynů. Pro výpočet bude potřeba přijmout celou řadu předpokladů týkajících se zejména budoucího vývoje fondu budov, energetického mixu v elektrické soustavě ČR a podílu energetických zdrojů v budovách.

2.2.3. Je tento potenciál dostačující z pohledu celosvětových limitů?

Vypočtený potenciál úspor bude vyhodnocen pomocí porovnání s národními limity vycházejícími z provedených rešerší.

2.2.4. Jak by vypadaly budovy splňující stanovené limity? Je to dosažitelné pomocí dnešního stavu techniky?

V případě, že se ukáže, že předpoklady scénářů úspor energie v budovách nejsou dostačující, bude zpracován návrh postupu na stanovení klimatických požadavků na jednotlivé budovy pro podmínky ČR. Následně bude možné odborně diskutovat nad možností, zda jsou tyto požadavky splnitelné a za jakých podmínek, a zda a jak by se měly aplikovat v běžné stavební praxi.

3. Současný stav poznání

3.1. Definice základních pojmů

3.1.1. Klima

Klima (podnebí) je dlouhodobý charakteristický režim počasí podmíněný energetickou bilancí, cirkulací atmosféry, charakterem aktivního povrchu a lidskou činností. Lze ho charakterizovat pomocí průměrných hodnot meteorologických prvků doplněných o extrémy a četnosti jejich výskytu, popřípadě o další statistické charakteristiky. Důležitým aspektem klimatu daného místa je také průměrný roční chod meteorologických prvků a jejich průměrná meziroční variabilita. (Katedra fyziky atmosféry MFF UK, 1970)

3.1.2. Klimatologie

Věda o klimatech Země, o podmínkách a příčinách jejich utváření a rovněž o působení klimatu na objekty činnosti člověka, na samotného člověka i na různé přírodní děje, a naopak. Jejím cílem je studovat obecné klimatické zákonitosti, genezi zemského klimatu a změny a kolísání klimatu (Ruda, 2014).

3.1.3. Monitorování stavu klimatu

Monitorování klimatu má dlouhou historii. Když v roce 1992 vznikla Rámcová úmluva OSN o změně klimatu, vznikla potřeba nezávislého monitorování stavu klimatu s veřejně dostupnými daty. Tato potřeba vyústila ve vznik organizace The Global Climate Observing System (GCOS), na jejímž provozu se podílí čtyři organizace: Světová meteorologická organizace (WMO), Mezivládní oceánografická komise v rámci UNESCO (IOC), Program OSN pro životní prostředí (UNEP) a Mezinárodní výbor pro vědu (ISC) (The Global Climate Observing System, 2019a).

GCOS používá sadu Global Climate Indicators, která obsahuje (The Global Climate Observing System, 2019b):

- Teplota a energie
  - Povrchová teplota (Surface Temperature)
  - Teplo v oceánech (Ocean Heat)
- Složení atmosféry
  - Atmosférický oxid uhličitý (Atmospheric CO_2)
- Oceány a vodstvo
  - Okyselení oceánů (Ocean Acidification)
  - Hladina moří (Sea Level)
- Kryosféra
  - Ledovce (Glaciers)
  - Rozsah arktického a antarktického zaledněnímoře (Arctic and Antarctic Sea Ice Extent)

3.1.4. Změna klimatu

Termín změna klimatu je legislativně definován v Rámcové úmluvě OSN o změně klimatu, která byla přijata na Konferenci OSN o životním prostředí a rozvoji v Rio de Janeiru v roce 1992. Tato úmluva „změnou klimatu rozumí takovou změnu klimatu, která je vázána přímo nebo nepřímo na lidskou činnost měnící složení globální atmosféry a která je vedle přirozené variability klimatu pozorována za srovnatelný časový úsek.“ (Ministerstvo zahraničních věcí ČR, 2005).

3.1.5. Adaptace a mitigace změny klimatu

Rozlišujeme dva způsoby reakce na změnu klimatu.

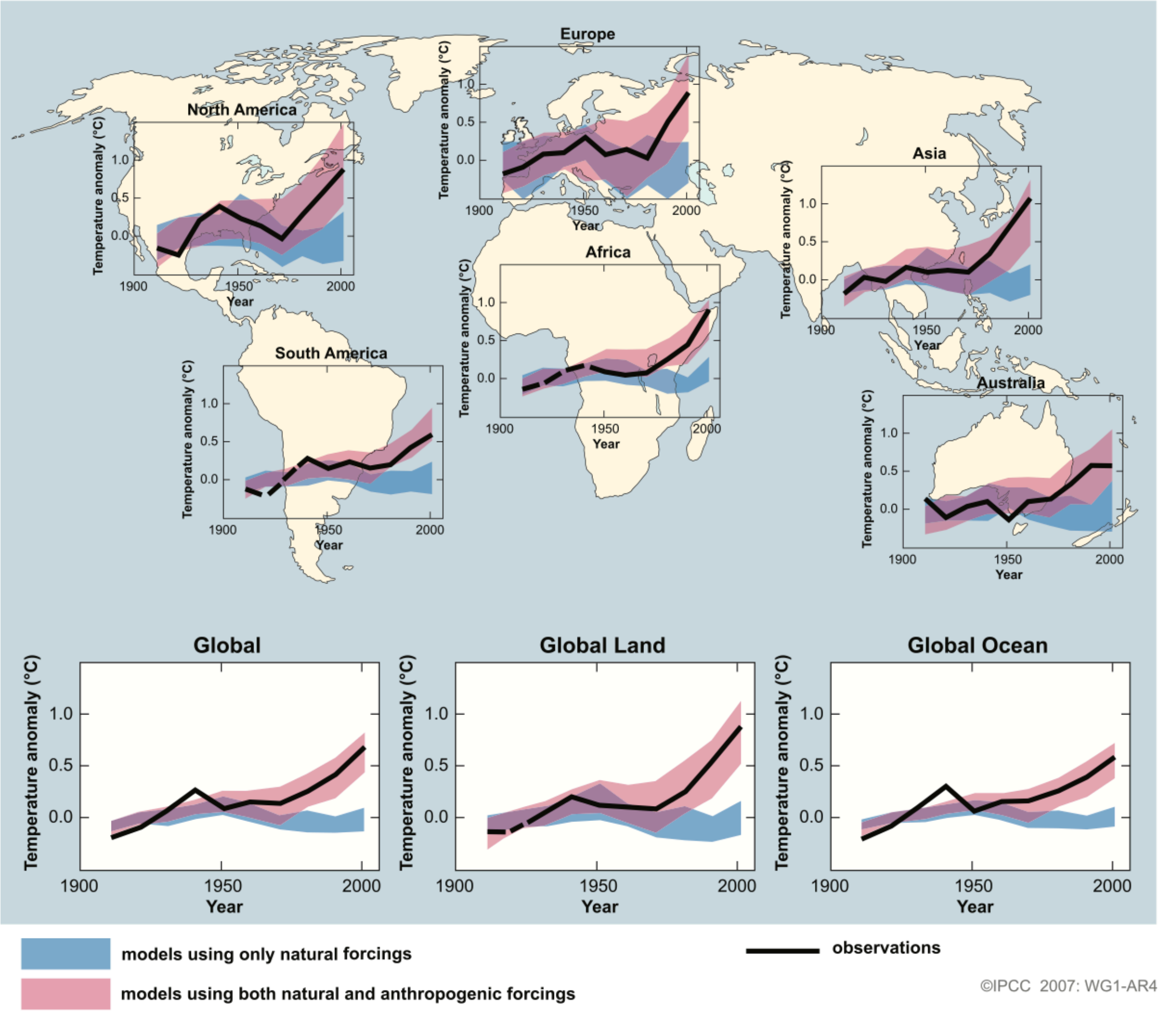
Prvním typem reakce je snaha zabránit prohlubování změny klimatu, zejména pomocí snižování produkce emisí skleníkových plynů nebo přímo aktivním zachytáváním skleníkových plynů z atmosféry a jejich dlouhodobému (ideálně trvalému) ukládání v různých formách. Takovéto chování se nazývá **mitigací** změny klimatu, prosazují se tzv. mitigační opatření.

Druhým způsobem reakce je snaha se přizpůsobit probíhající změně klimatu a jejím dopadům. Tato strategie se nazývá **adaptací** na změnu klimatu, prosazují se adaptační opatření.

Při současném vývoji je nezbytné věnovat se oběma strategiím, jak mitigaci, tak adaptaci. Tato práce je zaměřena na mitigační opatření.

3.1.6. Skleníkové plyny

Hlavní příčinou změny klimatu je změna složení zemské atmosféry. Přírodní a antropogenní plynné složky atmosféry, které absorbují a opětovně vyzařují infračervené záření (OSN, 1992) nazýváme skleníkovými plyny (GHG). Skleníkové plyny se v atmosféře vyskytují přirozeně i přičiněním lidské činnosti. Pokládá se za velmi pravděpodobné, že za současnou zrychlující změnou klimatu jsou právě vlivy člověka, především spalování fosilních paliv, ale i změny využití krajiny a další vlivy (například chladiva unikající do atmosféry). Tuto hypotézu ilustruje Obr. 1.



Obr. 1: Změny teploty oproti odpovídajícímu průměru za období 1901-1950 (°C) v jednotlivých desetiletích od roku 1906 do roku 2005 na zemských kontinentech, jakož i na celé zemi, na světové pevnině a ve světovém oceánu (spodní grafy). Černá čára označuje pozorované změny teploty, zatímco barevné pruhy znázorňují kombinovaný rozsah, který pokrývá 90 % nedávných modelových simulací. Červená barva označuje simulace, které zahrnují přírodní a lidské faktory, zatímco modrá barva označuje simulace, které zahrnují pouze přírodní faktory. Přerušované černé čáry označují desetiletí na kontinentálních oblastech, pro které je k dispozici podstatně méně pozorování (Core Writing Team, Pachauri and Reisigner, 2007).

3.1.7. Ekologická stopa

Koncept ekologické stopy byl poprvé popsán v devadesátých letech 20. století v pracích Wackernagela a Reese (Rees, 1992, 1996; Wackernagel and Rees, 1997), kdy bylo potřeba nějakým způsobem názorně popsat relativní význam ekologických dopadů lidské činnosti vzhledem k ekologickým limitům Země. Ekologická stopa byla zavedena jako plocha zemského povrchu, která je schopna absorbovat člověkem produkované škodliviny či poskytnout zdroje pro provoz civilizace. Typů stop je více, liší se podle toho, co se jimi měří (Fang, Heijungs and De Snoo, 2014, 2015). Uhlíková stopa je jednou z nich. Vývojem metodik ekologických stop se zabývá organizace Global Footprint Network (Global Footprint Network, 2018).

3.1.8. Uhlíková stopa

Uhlíková stopa je definována jako množství emisí ekvivalentů CO_2 přímo nebo nepřímo způsobených určitou aktivitou (Wiedmann and Minx, 2007) nebo jako celkové množství skleníkových plynů emitované během životního cyklu procesu nebo produktu (Carbon Trust and Defra, 2008).

3.1.9. Mezivládní panel pro změnu klimatu

Mezivládní panel pro změnu klimatu (Intergovernmental Panel on Climate Change, zkratka IPCC) je orgán OSN pro posuzování vědeckých výsledků souvisejících se změnou klimatu. Byl založen v roce 1988 ve spolupráci Světové meteorologické organizace (WMO) a UNEP. Poskytuje vládám členských zemí OSN informace o změně klimatu, pravidelné posudky vývoje vědeckých poznatků změny klimatu, jejích dopadů a budoucích rizik a možností adaptace a mitigace. Předkládané dokumenty (tzv. Assessment Reports, AR) slouží jako podklad pro tvorbu národních politik a jsou vstupem pro mezinárodní dohody. Práce IPCC je členěna do tří pracovních skupin (Working Groups) a jedné Task Force. Working Group I se zabývá vědeckým fyzikálním pozadím změny klimatu, Working Group II dopady změny klimatu, adaptací a náchylností ekosystémů a Working Group III mitigací změny klimatu. Hlavním úkolem Task Force on National Greenhouse Gas Inventories je vyvinout a vyladit metodiku pro výpočet a vykazování národních emisí skleníkových plynů (IPCC – The Intergovernmental Panel on Climate Change, no date). Hodnoticí zprávy AR vychází jednou za 5-7 let.

3.2. Očekávané dopady změny klimatu

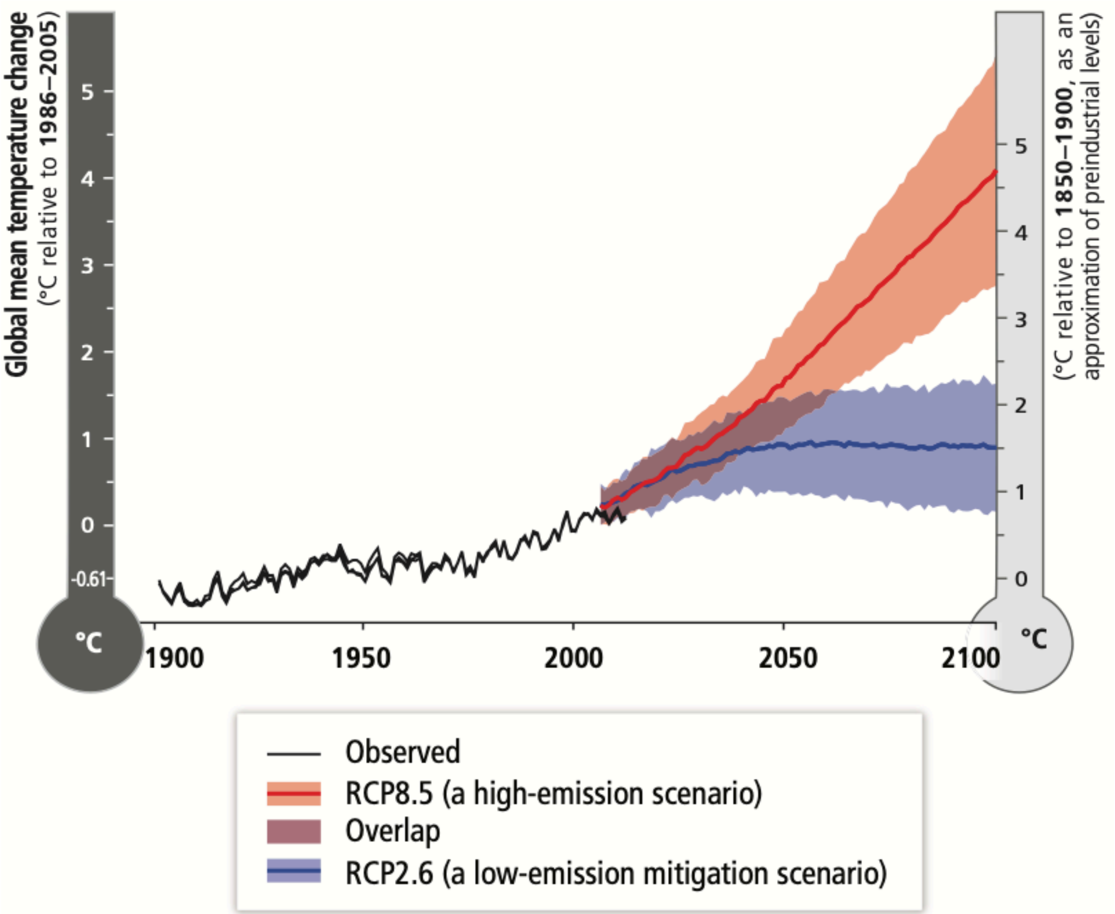
3.2.1. Klimatické modely a scénáře

Klimatický model představuje fyzikální, chemické a biologické procesy, které působí na klimatický systém (Core Writing Team, Pachauri and Reisigner, 2007). Problematiku klimatických modelů podrobně vysvětluje kapitola 9 AR5 (Flato *et al.*, 2013).

Klimatické scénáře na základě klimatických modelů popisují možné alternativy budoucího vývoje změny založené na různých kombinacích okrajových podmínek.

3.2.2. Očekávané dopady globální změny klimatu

Reporty IPCC pracují s tzv. Representative Concentration Pathways (zkratka RCP), neboli reprezentativními směry vývoje koncentrací skleníkových plynů. Ty stanovují, jak se bude vyvíjet koncentrace skleníkových plynů v atmosféře na základě vývoje společnosti, ekonomiky a mitigačních opatření. RCP 1.9 je scénář, který omezuje globální oteplování pod 1,5 °C v souladu s Pařížskou dohodou. RCP 2.4 předpokládá, že antropogenní emise skleníkových plynů budou vrcholit v roce 2020 a do roku 2100 se podaří dosáhnout nulových emisí. Dalším ze scénářů je RCP 4.5, který předpokládá, že emise skleníkových plynů nadále porostou, vyvrcholí v roce 2045, a poté budou do roku 2100 klesat zhruba na poloviční úroveň emisí roku 2050. Nejvíce pesimistickým scénářem je RCP 8.5, který uvažuje s tím, že by člověkem vypouštěné emise skleníkových plynů nebyly nijak omezovány. Rozsah modelovaných vzestupů průměrné povrchové teploty ve scénářích RCP 2.6 a RCP 8.5 je na Obr. 2.



Obr. 2: Historicky sledované a předpokládané vývoje povrchové teploty podle scénářů RCP 2.6 a RCP 8.5 (Field et al., 2014).

Výčet všech možných dopadů změny klimatu je nad rámec tohoto textu, podrobnosti k možnému vývoji jsou dostupné v dokumentech IPCC, shrnutí je k dispozici v *Technical Summary* k AR5 (Field *et al.*, 2014).

3.2.3. Očekávané dopady změny klimatu v Evropě

Současné předpovědi možných scénářů vývoje klimatu předpovídají v Evropě do roku 2100 nárůst průměrné roční teploty o 2-5 °C vzhledem k současnému stavu (van Engelen *et al.*, 2008). Změna klimatu se neprojeví stejnoměrně po celém kontinentu. Předpokládají se sušší letní období ve středomořské oblasti a deštivější zimy v severní Evropě. Dojde ke zvýšení mořské hladiny. Kromě změn podnebí se předpovídá nárůst počtu a intenzity krátkodobých vln veder, extrémních srážkových událostí a záplav (Barriopedro *et al.*, 2011; Giorgi *et al.*, 2011). Podrobná mapa dopadů po evropských regionech je dostupná v reportu EEA na str. 14 (European Environment Agency, 2012).

3.2.4. Předpokládané dopady změny klimatu na území ČR

Hodnocením zranitelnosti ČR vůči změně klimatu se pro MŽP podrobně zabývalo Centrum pro otázky životního prostředí Univerzity Karlovy s agenturou CENIA (Havránek and Ponocná, 2018; Mert *et al.*, 2018).

Studie *Rešerše klimatických modelů a studií dopadů změn klimatu* (Glopolis o.p.s., 2015) uvádí tato očekávání:

- *k roku 2030 se průměrná roční teplota vzduchu na našem území zvýší cca o 1 °C, průměrná roční teplota vzduchu v ČR stoupne do r. 2100 o několik stupňů*
- *zvýší se pravděpodobnost výskytu, intenzity i délky trvání episodických vln extrémně vysokých teplot*
- *vzroste počet tropických dní (nad 30 °C) a nocí (nad 20 °C)*
- *počet arktických (maximální teplota během dne nepřesáhne -10 °C), ledových (teplota se během celého dne drží pod bodem mrazu) a mrazových (minimální teplota během dne klesne pod bod mrazu) dnů bude klesat*
- *budou se zvyšovat zimní srážkové úhrny, letní srážkové úhrny budou naopak klesat, významně vzroste počet dnů bezesrážkového období a riziko vzniku sucha, zvýší se riziko vzniku požárů*
- *změny hydrologického cyklu – distribuce srážek: vzroste riziko přívalových dešťů a následných lokálních povodní, zvýší se maximální průtoky, ale nejspíše poklesnou průměrné a minimální průtoky řek, případně bude docházet k úplnému vyschnutí toku,*
- *vzroste riziko vzniku městských tepelných ostrovů.*

3.3. Ekologické limity s ohledem na změnu klimatu

3.3.1. Únosná kapacita

Termín únosná kapacita nebo též nosná kapacita se používá při prognózách růstu lidské populace a mezních dopadů, které tento růst může mít na životní prostředí při zachování funkčnosti základních ekosystémů (Seidl and Tisdell, 1999). Ty jsou třeba k přežití lidstva na zemi.

3.3.2. Klimatické limity

Klimatickými limity jsou v této práci myšleny ekologické limity vztahující se ke změně klimatu, které vyznačují meze únosné kapacity (fyzikální nebo stanovené dohodou). V Pařížské dohodě (United Nations, 2015), která se opírá o zprávy IPCC, jsou tyto meze převedeny na mezní únosnou míru změny klimatu, která je vymezená nárůstem teploty povrchu Země nad 1,5 °C v porovnání s předindustriální érou. Tato změna teploty je považována za mez, kdy se začne klima výrazně měnit, s dopady jak na přírodu, tak na člověka. Za hranici, kdy pravděpodobně začne docházet k nevratným změnám je považována hranice 2,0 °C. V roce 2020 byl svět na trajektorii vedoucí k vzestupu teploty přibližně o 3 °C do konce 21. století.

3.3.3. Uhlíkový rozpočet

Uhlíkový rozpočet je pomyslné maximální množství skleníkových plynů, které je ještě možné vypustit do atmosféry, aniž by byl překročen určitý klimatický limit (Meinshausen *et al.*, 2009). Různé zdroje uvádějí různou výši zbývajícího uhlíkového rozpočtu. Ten se vyvíjí podle stavu poznání a s časem se zmenšuje s tím, jak roste koncentrace skleníkových plynů v atmosféře. Výše uváděného uhlíkového rozpočtu se také liší podle toho, zda připouštíme možnost, že v budoucnu bude technicky možné skleníkové plyny z atmosféry zachycovat a ukládat (problematika carbon capture and storage, CCS). V takovém případě by bylo možné o něco déle pokračovat v emitování skleníkových plynů v první polovině století a později emise zpět z atmosféry odebrat.

Tab. 1: Celkový zbývající globální rozpočet uhlíku vyjádřený v Gt $CO_{2,ekv.}$ Podle (Williges et al., 2019). Scénář *Pravděpodobně pod 2 °C* je v souladu s 5. hodnotící zprávou IPCC citovanou v (Rogelj et al., 2016) 50 % pod 2 °C. Scénář *Výrazně pod 2 °C* vychází z (Rockström et al., 2017) s více než 66 % pod 2 °C. Scénář *Cíl 1,5 °C* je definován podle (Millar et al., 2017) s 50 % pod 1,5 °C.

Scénáře		2020-2050	2050-2010
Bez uvažování negativních emisí	Cíl 1,5 °C	500	0
	Výrazně pod 2 °C	700	0
	Pravděpodobně pod 2 °C	1 100	0
S uvažováním negativních emisí	Cíl 1,5 °C	1 700	-1 200
	Výrazně pod 2 °C	1 900	-1 200
	Pravděpodobně pod 2 °C	2 300	-1 200

3.3.4. Klimatické požadavky na budovy

Pro účel této práce jsou klimatické požadavky na budovu (či soubor budov nebo fond budov) chápány jako takové požadavky na emise skleníkových plynů nebo emise oxidu uhličitého, které zajistí, že při jejich dodržení pro budovu (či soubor budov nebo fond budov) nedojde k překročení klimatických limitů stanovených pro budovy na sledovaném území.

Může se jednat pouze o provozní produkci skleníkových plynů, ale mohou být zahrnuta i množství skleníkových plynů vznikající při těžbě a zpracování surovin při výrobě stavebních materiálů, jejich dopravě a zabudování na stavbě, pravidelné údržbě až po odstraňování dosloužilých budov (tedy dopady celého životního cyklu budov).

3.3.5. Uhlíkový rozpočet budovy

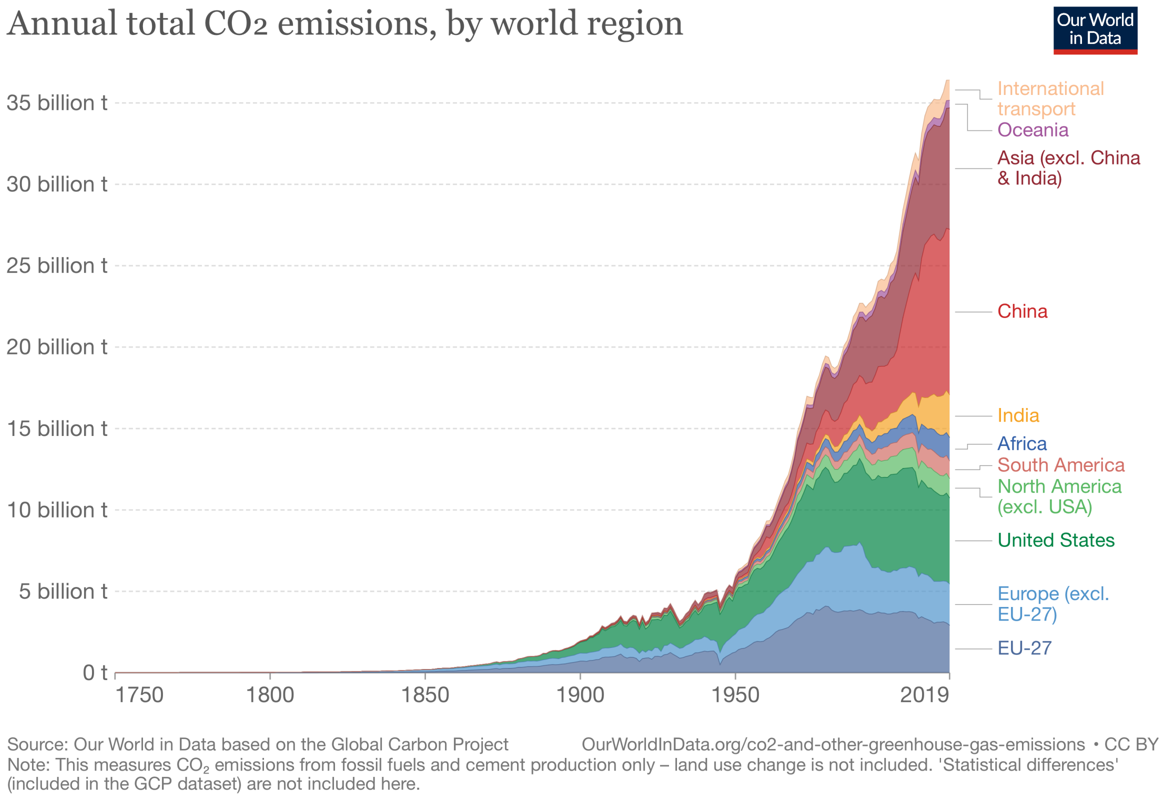
Uhlíkový rozpočet budovy v kontextu této práce představuje podíl na globálním uhlíkovém rozpočtu alokovaný na úroveň budovy.

3.4. Vývoj antropogenních emisí skleníkových plynů

Následující kapitoly dávají stručný přehled o vývoji emisí skleníkových plynů v důsledku činnosti člověka.

3.4.1. Vývoj globální produkce skleníkových plynů

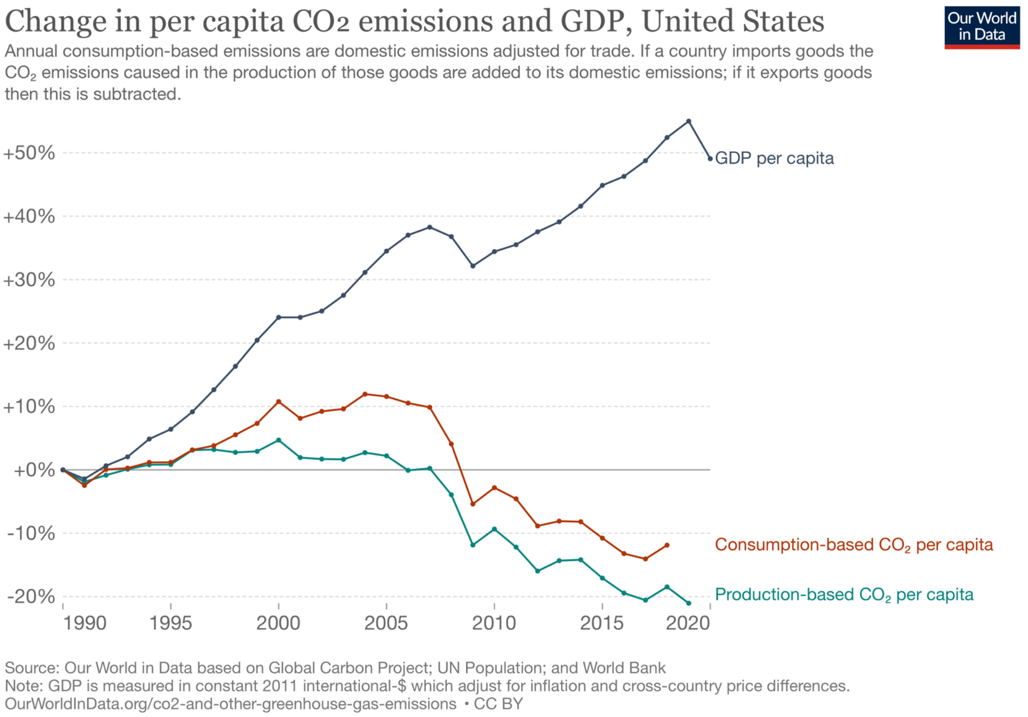
V následujícím Obr. 3 je uveden vývoj globálních emisí skleníkových plynů v letech 1750-2019, tmavě modrá barva dole v grafu vyznačuje podíl EU. Z grafu je vidět, že emisím skleníkových plynů dominuje Čína a USA, EU byla v roce 2019 zodpovědná za přibližně 16 % emisí skleníkových plynů. Produkce skleníkových plynů je celosvětově nevyrovnaná.


Annual total CO2 emissions, by world region

Source: Our World in Data based on the Global Carbon Project OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY
Note: This measures CO_2 emissions from fossil fuels and cement production only – land use change is not included. 'Statistical differences' (included in the GCP dataset) are not included here.

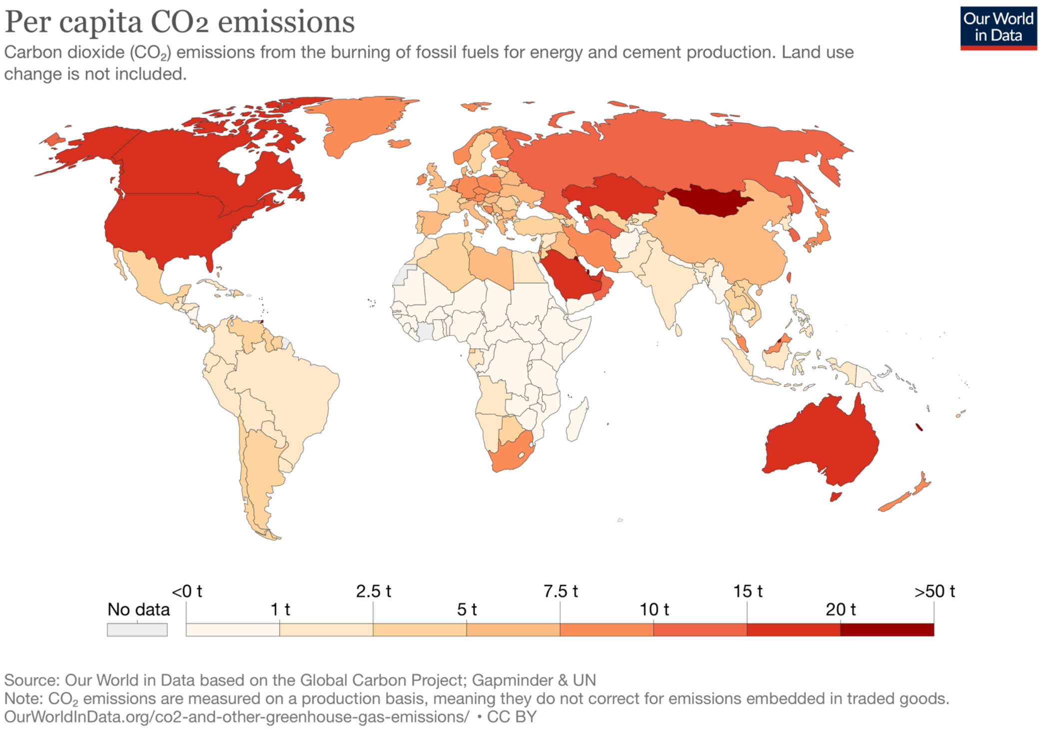
Obr. 3: Vývoj světových emisí skleníkových plynů (Ritchie and Roser, 2020).

V minulosti byly trendy produkce skleníkových plynů jednotlivých států přibližně lineárně navázány na jejich HDP. V poslední době se však tyto křivky díky zvýšené energetické efektivitě technologií a přechodu na obnovitelné či jiné bezemisní zdroje energie začínají rozpojovat. Příkladem tohoto jevu je vývoj v USA, jež je zobrazen na Obr. 4.



Obr. 4: Rozpojení růstu HDP od emisí skleníkových plynů v USA (Ritchie and Roser, 2020).

Cílem snah o ochranu klimatu je toto rozpojení zajistit ve všech státech a významně jej urychlit. Zároveň je ovšem třeba zajistit, aby tím nebyla ohrožena životní úroveň – aby jednostranně orientované snahy na snižování emisí skleníkových plynů nevedly v důsledku ke zhoršení kvality života, ekonomické stability, ohrožení občanských svobod a dalších společenských hodnot. To by hrozilo zejména ve státech, které by byly donuceny rapidně snížit svou uhlíkovou stopu. Tuto situaci ilustruje Obr. 5 zobrazující emise skleníkových plynů přepočtené na obyvatele.

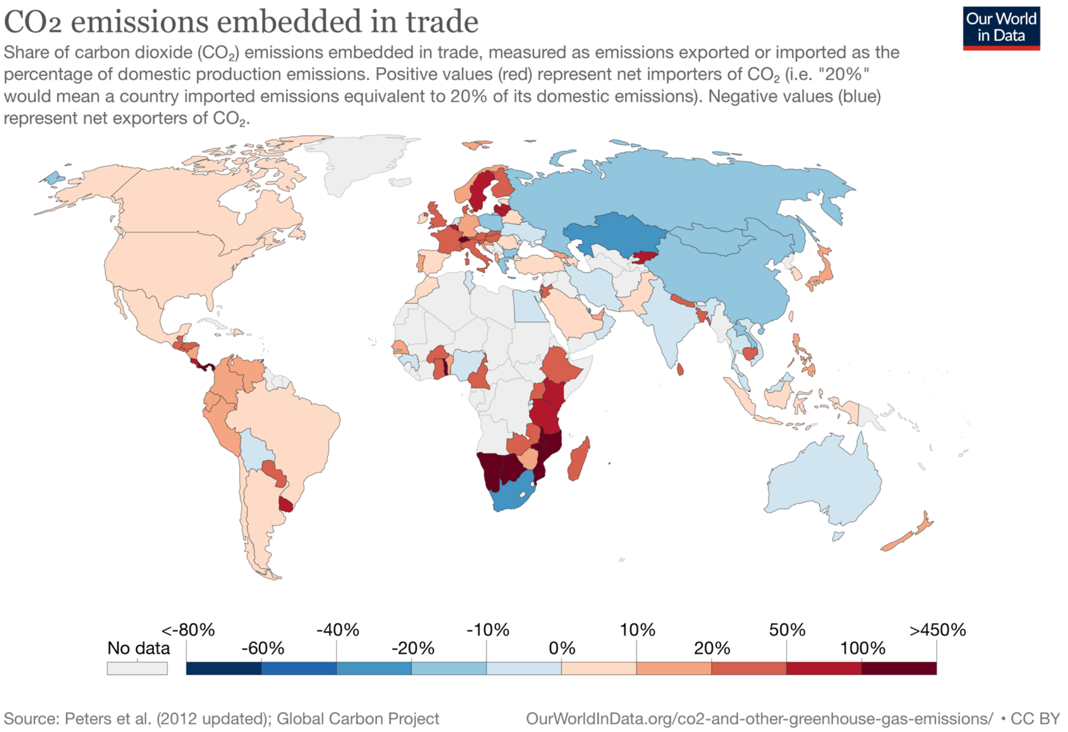

Per capita CO2 emissions

Carbon dioxide (CO_2) emissions from the burning of fossil fuels for energy and cement production. Land use change is not included.

Source: Our World in Data based on the Global Carbon Project; Gapminder & UN
Note: CO_2 emissions are measured on a production basis, meaning they do not correct for emissions embedded in traded goods.
OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY

Obr. 5: Emise skleníkových plynů v jednotlivých státech přepočtené na obyvatele. Světový průměr byl v roce 2017 4,8 tun CO_2/obyv. (Ritchie and Roser, 2020).

Dalším problémem, který je v současné době hodně citován je přesouvání energeticky a materiálově náročné výroby do třetích zemí. Problémem jsme se podrobněji zabývali s kolegy z přírodovědecké fakulty v roce 2015 (Vlčková *et al.*, 2015). Aktuální stav z roku 2018 je na Obr. 6, ze kterého je vidět, které státy ve výrobcích emise dovážejí a které vyvážejí. Oproti tomuto trendu bude působit deglobalizace v důsledku COVID, kdy řada firem přemýšlí o přesunutí výroby zpět blíže ke koncové výrobě a zákazníkům. Na druhou stranu, nešikovně zavedené a řízené zdanění emisí skleníkových plynů může tento problém ještě prohloubit. Řešením by mohlo být zavedení uhlíkového cla, jak dlouhodobě navrhuje nobelista William Nordhaus (Nordhaus, 2015), a o kterém Evropská unie v posledním roce nahlas uvažuje. Zavedení cel na zboží ze zemí, kde nejsou uhlíkové emise zdaněny může výrazně pomoci, problémem ale bude nárůst cen spotřebního zboží. Bude tedy nutné tato opatření zavádět velmi citlivě a dobře navrhnout mechanismy, jak vybranou daň jiným způsobem vrátit ekonomicky slabým spoluobčanům, jinak hrozí prohloubení chudoby a nerovností ve společnosti.



CO2 emissions embedded in trade

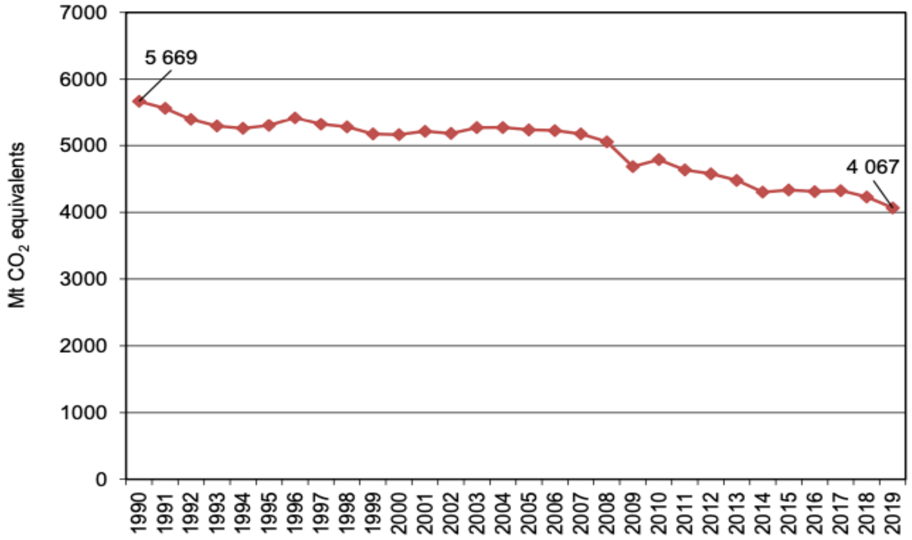
Share of carbon dioxide (CO_2) emissions embedded in trade, measured as emissions exported or imported as the percentage of domestic production emissions. Positive values (red) represent net importers of CO_2 (i.e. "20%" would mean a country imported emissions equivalent to 20% of its domestic emissions). Negative values (blue) represent net exporters of CO_2.

Source: Peters et al. (2012 updated); Global Carbon Project OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY

Obr. 6: Emise skleníkových plynů v jednotlivých státech přepočtené na obyvatele. Světový průměr byl v roce 2017 4,8 tun CO2/obyv. (Ritchie and Roser, 2020).

3.4.2. Vývoj Evropské produkce skleníkových plynů

Vývoj produkce skleníkových plynů v EU sleduje Evropská agentura pro životní prostředí (EEA), která je zároveň zodpovědná za předkládání zpráv UNFCCC v souladu s metodikou podle Kjótského protokolu. Stav k roku 2019 ukazuje graf na Obr. 7, podíl států EU je v Tab. 2.



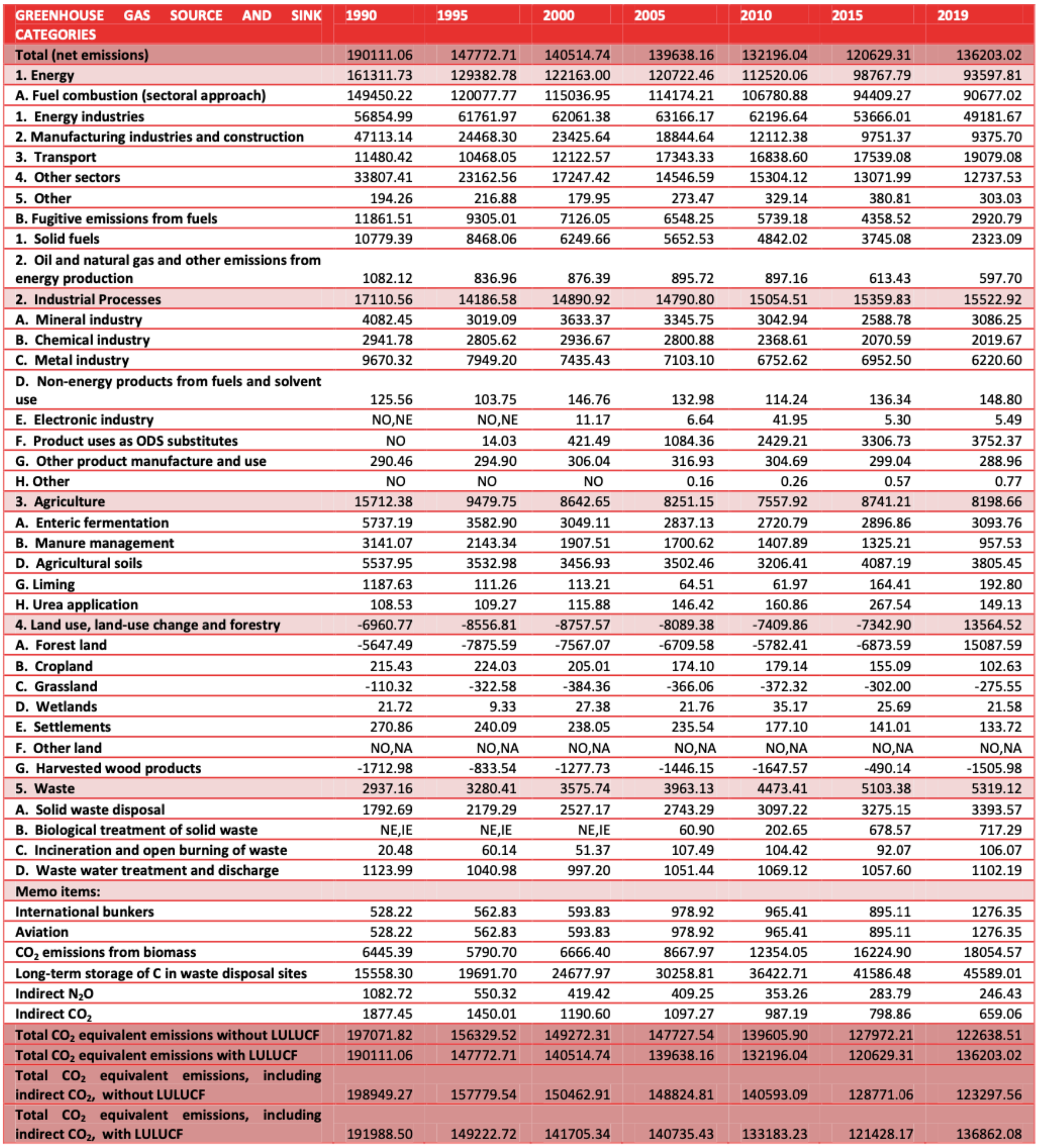
Obr. 7: Vývoj produkce emisí skleníkových plynů v EU-27, Islandu a Spojeném království v roce 2019 bez zahrnutí LULUCF (European Commission, DG Climate Action and European Environment Agency, 2021).

Tab. 2: Emise skleníkových plynů jednotlivých zemí EU a Spojeného království v letech 1990 a 2019 v milionech tun CO2,ekv. bez LULUCF (European Commission, DG Climate Action and European Environment Agency, 2021)

Země	1990	2019	Změna 1990-2019
Belgie	145,7	116,7	-19,9 %
Bulharsko	100,0	56,0	-44,0 %
Česko	198,9	123,3	-38,0 %
Dánsko	70,9	44,2	-37,6 %
Estonsko	41,0	14,7	-64,2 %
Finsko	71,2	53,1	-25,5 %
Francie	544,0	436,0	-19,9 %
Chorvatsko	31,4	23,6	-24,8 %
Irsko	54,4	59,8	9,9 %
Island	3,7	4,7	28,2 %
Itálie	518,7	418,3	-19,4 %
Kypr	5,6	8,8	58,7 %
Litva	47,8	20,4	-57,4 %
Lotyšsko	25,9	11,1	-57,0 %
Lucembrusko	12,7	10,7	-15,6 %
Maďarsko	94,8	64,4	-32,0 %
Malta	2,6	2,2	-16,2 %
Německo	1 248,6	809,8	-35,1 %
Nizozemsko	220,5	180,7	-18,0 %
Polsko	475,9	390,7	-17,9 %
Portugalsko	58,9	63,6	8,1 %
Rakousko	78,4	79,8	1,8 %
Rumunsko	266,4	113,9	-57,3 %
Řecko	103,3	85,6	-17,1 %
Slovensko	73,5	40,0	-45,6 %
Slovinsko	18,6	17,1	-8,2 %
Spojené království	794,1	452,3	-43,0 %
Španělsko	290,0	314,5	8,5 %
Švédsko	71,2	50,9	-28,5 %
EU	**5668,7**	**4067,1**	**-28,3 %**

3.4.3. Vývoj národní produkce skleníkových plynů

Emise skleníkových plynů za Česko pravidelně reportuje Český hydrometeorologický ústav (ČHMÚ) na základě *Nařízení Evropského parlamentu a Rady (EU) č. 525/2013 ze dne 21. května 2013 o mechanismu monitorování a vykazování emisí skleníkových plynů a podávání dalších informací na úrovni členských států a Unie vztahujících se ke změně klimatu a o zrušení rozhodnutí č. 280/2004/ES (1) a dále Sekretariátu Rámcové úmluvy OSN o změně klimatu v rámci Kjótského protokolu* (Ústav, no date). V době psaní této práce (srpen 2021) je k dispozici kompletní Národní inventarizační zpráva (NIR) zveřejněná v dubnu 2021, která poskytuje data k emisím do roku 2019 (Krtková *et al.*, 2021). Z ní pochází následující souhrnná tabulka na Obr. 8.



GREENHOUSE GAS SOURCE AND SINK CATEGORIES	1990	1995	2000	2005	2010	2015	2019
Total (net emissions)	190111.06	147772.71	140514.74	139638.16	132196.04	120629.31	136203.02
1. Energy	161311.73	129382.78	122163.00	120722.46	112520.06	98767.79	93597.81
A. Fuel combustion (sectoral approach)	149450.22	120077.77	115036.95	114174.21	106780.88	94409.27	90677.02
1. Energy industries	56854.99	61761.97	62061.38	63166.17	62196.64	53666.01	49181.67
2. Manufacturing industries and construction	47113.14	24468.30	23425.64	18844.64	12112.38	9751.37	9375.70
3. Transport	11480.42	10468.05	12122.57	17343.33	16838.60	17539.08	19079.08
4. Other sectors	33807.41	23162.56	17247.42	14546.59	15304.12	13071.99	12737.53
5. Other	194.26	216.88	179.95	273.47	329.14	380.81	303.03
B. Fugitive emissions from fuels	11861.51	9305.01	7126.05	6548.25	5739.18	4358.52	2920.79
1. Solid fuels	10779.39	8468.06	6249.66	5652.53	4842.02	3745.08	2323.09
2. Oil and natural gas and other emissions from energy production	1082.12	836.96	876.39	895.72	897.16	613.43	597.70
2. Industrial Processes	17110.56	14186.58	14890.92	14790.80	15054.51	15359.83	15522.92
A. Mineral industry	4082.45	3019.09	3633.37	3345.75	3042.94	2588.78	3086.25
B. Chemical industry	2941.78	2805.62	2936.67	2800.88	2368.61	2070.59	2019.67
C. Metal industry	9670.32	7949.20	7435.43	7103.10	6752.62	6952.50	6220.60
D. Non-energy products from fuels and solvent use	125.56	103.75	146.76	132.98	114.24	136.34	148.80
E. Electronic industry	NO,NE	NO,NE	11.17	6.64	41.95	5.30	5.49
F. Product uses as ODS substitutes	NO	14.03	421.49	1084.36	2429.21	3306.73	3752.37
G. Other product manufacture and use	290.46	294.90	306.04	316.93	304.69	299.04	288.96
H. Other	NO	NO	NO	0.16	0.26	0.57	0.77
3. Agriculture	15712.38	9479.75	8642.65	8251.15	7557.92	8741.21	8198.66
A. Enteric fermentation	5737.19	3582.90	3049.11	2837.13	2720.79	2896.86	3093.76
B. Manure management	3141.07	2143.34	1907.51	1700.62	1407.89	1325.21	957.53
D. Agricultural soils	5537.95	3532.98	3456.93	3502.46	3206.41	4087.19	3805.45
G. Liming	1187.63	111.26	113.21	64.51	61.97	164.41	192.80
H. Urea application	108.53	109.27	115.88	146.42	160.86	267.54	149.13
4. Land use, land-use change and forestry	-6960.77	-8556.81	-8757.57	-8089.38	-7409.86	-7342.90	13564.52
A. Forest land	-5647.49	-7875.59	-7567.07	-6709.58	-5782.41	-6873.59	15087.59
B. Cropland	215.43	224.03	205.01	174.10	179.14	155.09	102.63
C. Grassland	-110.32	-322.58	-384.36	-366.06	-372.32	-302.00	-275.55
D. Wetlands	21.72	9.33	27.38	21.76	35.17	25.69	21.58
E. Settlements	270.86	240.09	238.05	235.54	177.10	141.01	133.72
F. Other land	NO,NA	NO,NA	NO,NA	NO,NA	NO,NA	NO,NA	NO,NA
G. Harvested wood products	-1712.98	-833.54	-1277.73	-1446.15	-1647.57	-490.14	-1505.98
5. Waste	2937.16	3280.41	3575.74	3963.13	4473.41	5103.38	5319.12
A. Solid waste disposal	1792.69	2179.29	2527.17	2743.29	3097.22	3275.15	3393.57
B. Biological treatment of solid waste	NE,IE	NE,IE	NE,IE	60.90	202.65	678.57	717.29
C. Incineration and open burning of waste	20.48	60.14	51.37	107.49	104.42	92.07	106.07
D. Waste water treatment and discharge	1123.99	1040.98	997.20	1051.44	1069.12	1057.60	1102.19
Memo items:							
International bunkers	528.22	562.83	593.83	978.92	965.41	895.11	1276.35
Aviation	528.22	562.83	593.83	978.92	965.41	895.11	1276.35
CO_2 emissions from biomass	6445.39	5790.70	6666.40	8667.97	12354.05	16224.90	18054.57
Long-term storage of C in waste disposal sites	15558.30	19691.70	24677.97	30258.81	36422.71	41586.48	45589.01
Indirect N_2O	1082.72	550.32	419.42	409.25	353.26	283.79	246.43
Indirect CO_2	1877.45	1450.01	1190.60	1097.27	987.19	798.86	659.06
Total CO_2 equivalent emissions without LULUCF	197071.82	156329.52	149272.31	147727.54	139605.90	127972.21	122638.51
Total CO_2 equivalent emissions with LULUCF	190111.06	147772.71	140514.74	139638.16	132196.04	120629.31	136203.02
Total CO_2 equivalent emissions, including indirect CO_2, without LULUCF	198949.27	157779.54	150462.91	148824.81	140593.09	128771.06	123297.56
Total CO_2 equivalent emissions, including indirect CO_2, with LULUCF	191988.50	149222.72	141705.34	140735.43	133183.23	121428.17	136862.08

Obr. 8: Souhrn emisí skleníkových plynů v ČR mezi lety 1990 a 2019 v kt $CO_{2,ekv.}$ (Krtková et al., 2021).

3.5. Současné názory na principy distribuce ekologických limitů

V této kapitole jsou použity vybrané texty ze společného článku *Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions*, který vznikl v rámci mezinárodní spolupráce v IEA EBC Annex 72 (Habert *et al.*, 2020).

Jak bylo uvedeno v předchozích kapitolách, emise skleníkových plynů doposud rostly. Pro splnění emisního cíle 1,5 °C by bylo potřeba, aby emise v těchto letech vrcholily a začaly nadále klesat, to se ale přirozenou cestou nedaří. Hledají se tedy mechanismy, jak rozdělit zodpovědnost mezi státy a mezi ekonomické sektory a vytvořit závazky ke snižování emisí skleníkových plynů.

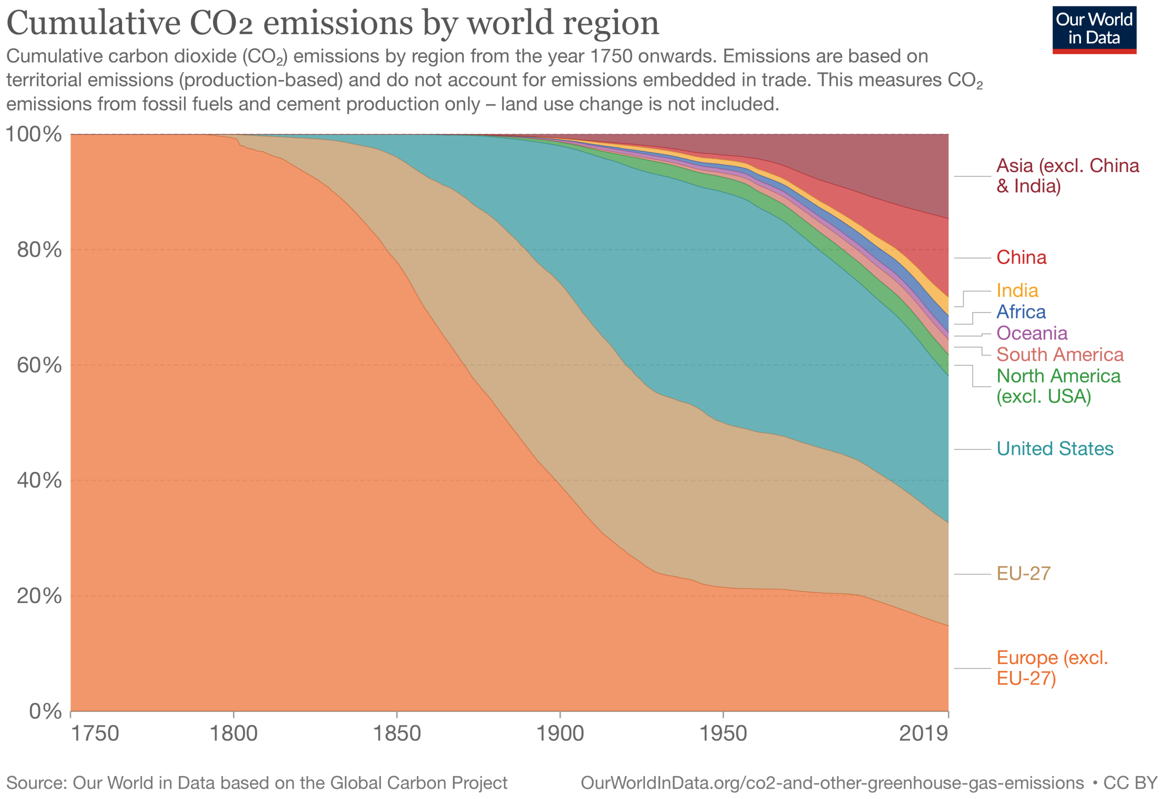
Je potřeba, aby vnímání závazků bylo vnímáno jako spravedlivé, jinak hrozí, že by vzniklé závazky nebyly dodrženy. Nalezení shody na přístupu, který by byl spravedlivý, není jednoduché, v tomto kontextu vznikl i pojem klimatická spravedlnost (climate justice).

K rozdělení závazků je možné použít uhlíkový rozpočet (viz kap. 3.3.3), který lze teoreticky alokovat konkrétním zodpovědným subjektům: národním státům, municipalitám, ale i jednotlivcům či ekonomickým sektorům. Rozčlenění celkového rozpočtu na rozpočet pro jednotlivé zúčastněné strany (nebo oblasti činností) zahrnuje dva rozměry: specifikaci úrovně členění (od země po osobu) a účetní princip, který určuje, jaká část rozpočtu se spotřebuje na konkrétní činnosti. Obvyklou první úrovní členění je členění podle zemí, v rámci kterého lze rozpočet dále členit např. podle hospodářských odvětví, oblastí potřeb nebo podle počtu obyvatel.

V literatuře se o alokačních mechanismech hovoří především v případě členění na úrovni jednotlivých zemí (Alcaraz *et al.*, 2019). Čím menší je rozpočet přidělený dané zemi ve vztahu k současným emisím, tím větší úsilí o zmírnění emisí se pro danou zemi předpokládá. Alokační mechanismy lze dělit na základě tří principů spravedlnosti: odpovědnosti, schopnosti a rovnosti a jejich různých kombinací, jak je uvedeno v IPCC AR5 (Clarke *et al.*, 2014).

- ***Zodpovědnost:*** týká se toho, zda jsou zohledněny historické emise. Pokud ano, jejich nadměrný výskyt snižuje podíl země na globálním rozpočtu, který k dnešnímu dni ještě zbývá.
- ***Schopnost:*** vychází ze zásady UNFCCC, že země by měly jednat "v souladu se svými společnými, ale diferencovanými povinnostmi a příslušnými schopnostmi a sociálními a ekonomickými podmínkami" (UN, 1992). Při rozdělování rozpočtu to znamená větší podíl rozpočtu pro země, které se nacházejí na nižších příčkách v ukazatelích jako je HDP nebo index lidského rozvoje (HDI).
- ***Rovnost:*** často znamená "přidělování na základě okamžitých nebo konvergujících emisí na obyvatele" (Clarke *et al.*, 2014). Okamžitá rovnost v přepočtu na obyvatele rozděluje zbývající část globálního rozpočtu zemím na základě počtu jejich obyvatel. Rovnost, která konverguje k budoucímu časovému bodu (možná až k roku 2050), zahrnuje druh "grandfatheringu", který uznává, že současné země s vysokými emisemi potřebují čas na přechod. Tím se však přisuzuje legitimita současnému stavu vysoce nerovných úrovní emisí, a dokonce se ospravedlňuje jejich další přetrvávání. Tento přístup zajišťuje, že vysoce průmyslově vyspělé země mají v přechodném období mnohem více emisních práv, což ovšem konzervuje současnou nerovnost (Williges et al. 2019).

S principem historické zodpovědnosti velmi pravděpodobně souvisí současné snahy Evropské unie o vedoucí úlohu ve snižování emisí skleníkových plynů. Existují dopočty, kolik emisí skleníkových plynů jednotlivé země vypustily do atmosféry od začátku průmyslové revoluce, výsledky jsou zobrazeny na Obr. 9.



Cumulative CO2 emissions by world region

Cumulative carbon dioxide (CO_2) emissions by region from the year 1750 onwards. Emissions are based on territorial emissions (production-based) and do not account for emissions embedded in trade. This measures CO_2 emissions from fossil fuels and cement production only – land use change is not included.

Source: Our World in Data based on the Global Carbon Project OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

Obr. 9: Historický dopočet kumulativních emisí CO_2 (Ritchie and Roser, 2020).

Problematikou přerozdělování uhlíkového rozpočtu se zabývaly i další práce (Bastianoni, Pulselli and Tiezzi, 2004; Höhne, den Elzen and Escalante, 2014; Steininger *et al.*, 2014, 2016).

3.6. Mezinárodní úmluvy vedoucí k mitigaci změny klimatu

3.6.1. Rámcová úmluva OSN o změně klimatu

V roce 1992 byla na Konferenci OSN o životním prostředí a rozvoji v Rio de Janeiru podepsána Rámcová úmluva OSN o změně klimatu (anglicky United Nations Framework Convention on Climate Change, UNFCCC, (OSN, 1992)), která poskytuje rámec mezinárodním vyjednávání o možném řešení problémů spojených s probíhající změnou klimatu, včetně problematiky snižování emisí skleníkových plynů, vyrovnávání se s negativními dopady změny klimatu i finanční a technologické podpory rozvojovým zemím (Ministerstvo životního prostředí, 2019). Rámcová úmluva OSN o změně klimatu vešla v platnost 21. 3. 1994 a ke dnešnímu dni ji ratifikovalo 197 zemí (United Nations Climate Change, 2014).

Agendu UNFCCC, a na ní navazující mezinárodní dohody, má na starost její sekretariát s názvem United Nations Climate Change, který od roku 1995 sídlí v Bonnu. Sekretariát pořádá každoročně několik mezinárodních akcí, z nichž nejvýznamnější je Konference smluvních stran (Conference of Parties, COP) (United Nations Climate Change, 2019). Mezi dosud nejvýznamnější COP patří COP7, na které byl schválen Kjótský protokol a COP21, na které byla schválena Pařížská dohoda.

3.6.2. Kjótský protokol

Kjótský protokol je mezinárodní smlouva k Rámcové úmluvě OSN o změně klimatu, která zavazovala smluvní strany ke stanovení mezinárodně závazných cílů snižování produkce skleníkových plynů. Protokol zohledňoval fakt, že za vysoké koncentrace skleníkových plynů v atmosféře jsou zodpovědné především rozvinuté země.

Kjótský protokol byl přijat v Kjótu 11. 12. 1997. Detailní pravidla implementace byla schválena na COP7 v Marakéši v roce 2001 a ratifikovalo ho 132 zemí. Protokol vstoupil v platnost 16. 2. 2005 a stanovoval limity na produkci šesti skleníkových plynů pro první období v letech 2008-2012 s cílem snížení o 5 % oproti roku 1990. V roce 2012 vzniknul v Dauhá Dodatek 1, který stanovil limity pro období 2013-2020 s cílem snížení ročních emisí o 18 % oproti roku 1990. Primárním cílem Kjótského protokolu je především snížení emisí skleníkových plynů na vlastním území, Protokol však umožňuje část závazku splnit pomocí flexibilních mechanismů, které umožňují plnění na území jiného státu či odkup nevyčerpaných limitů od jiných států (UNFCCC, 1997). Od roku 2005 se v rámci každoročních konferencí COP obvykle koná i setkání signatářů Kjótského protokolu (Conference of the Parties Serving as the Meeting of Parties to the Kyoto Protocol), používá se pro ně zkratka CMP.

3.6.3. Pařížská dohoda

Pařížská dohoda, která byla schválena během klimatické konference v Paříži 2015 (COP21), nahradí Kjótský protokol. Cílem Dohody je posílit globální odezvu na hrozbu změny klimatu opatřeními k udržení nárůstu globální teploty výrazně pod 2 °C oproti období před průmyslovou revolucí a usilovat o to, aby tento nárůst nepřekročil 1,5 °C. Dohoda ukládá všem státům stanovit si národní příspěvky k dosažení dílu dohody (United Nations, 2015). Od roku 2016 se konají pravidelné konference signatářů Pařížské dohody (Conference of the Parties serving as the meeting of the Parties to the Paris Agreement, zkratka CMA), které jsou přidruženy ke konferencím COP.

3.6.4. Marakéšské partnerství pro globální klimatické akce

Partnerství (v originále Marrakech Partnership for Global Climate Action) bylo spuštěno na COP22 v roce 2016. Cílem Partnerství je podpořit Pařížskou dohodu podporou aktivit nastavením multilaterální komunikace různých koalic, iniciativ a organizací (tedy ne-členů Pařížské dohody, jejímiž signatáři jsou národní státy) s cílem aktivizovat klíčové hráče k rychlejšímu postupu v mitigaci změny klimatu tak, aby bylo možné dosáhnout dlouhodobých cílů Pařížské konference, a tak umožnit dosažení cílů udržitelného rozvoje OSN (SDGs) (UNFCCC, 2017).

3.6.5. Závazek EU vůči Pařížské dohodě

Jednotlivé státy dobrovolně předkládají Národní klimatické plány (United Nations Framework Convention on Climate Change, 2021). Státy Evropské unie se dohodly, že budou předkládat národní klimatické plány společně. Česká republika vůči spojeným národům splnila předložení závazku prostřednictvím společného závazku členských států, který Evropská unie předložila během Lotyšského předsednictví v roce 2015 (UNFCC, 2021). V něm se EU dobrovolně zavázala do roku 2030 snížit emise skleníkových plynů o 40 % oproti roku 1990. Indikátorem jsou ekvivalentní emise skleníkových plynů podle Montrealského protokolu (tedy celkem 7 plynů). Mechanismus vedoucí ke splnění závazku řeší nařízení Evropského parlamentu a Rady (EU) 2018/1999.

V roce 2020 během německého předsednictví se EU dohodla na směřování k uhlíkové neutralitě v roce 2050 a zároveň k cíli snížení emisí skleníkových plynů v roce 2030 o 55 % oproti roku 1990 (European Commission, 2020).

3.6.6. EU Green Deal – Zelená dohoda pro Evropu

Zelená dohoda pro Evropu (European Council, 2021a) je ambiciózní plán transformace EU na konkurenceschopnou klimaticky neutrální ekonomiku. Obsahuje soubor opatření, která mají podpořit účinné využívání zdrojů prostřednictvím přechodu na čisté oběhové hospodářství, zabránit ztrátě biologické rozmanitosti a snížit znečištění.

Prostředkem, jak naplnit cíle Green Deal, je připravovaný balíček legislativních opatření Fit for 55 (European Council, 2021b), jehož název je odvozen z klimatického cíle redukce produkce skleníkových plynů EU o 55 % do roku 2030 (oproti roku 1990).

3.6.7. Klimatické politiky a závazky ČR

Základním národním dokumentem k mitigaci změny klimatu je Politika ochrany klimatu v ČR, která byla schválena usnesením vlády v roce 2017, které zároveň ukládá státní správě se dokumentem řídit (Ministerstvo životního prostředí České republiky, 2017). Hlavními cíli Politiky ochrany klimatu v ČR bylo stanovit vhodný mix nákladově efektivních opatření a nástrojů v klíčových sektorech vedoucí ke snížení emisí ČR do roku 2020 alespoň o 32 Mt $CO_{2,ekv.}$ a do roku 2030 alespoň o 44 Mt $CO_{2,ekv.}$ v porovnání s rokem 2005. Dlouhodobými indikativními cíli Politiky ochrany klimatu v ČR je směřovat k úrovni 70 Mt $CO_{2,ekv.}$ vypouštěných emisí v roce 2040 a 39 Mt $CO_{2,ekv.}$ v roce 2050. Politika ochrany klimatu také stanovila Závazky ČR zohledňující závazky EU vázající se na emise skleníkových plynů vypouštěných Českem v roce 1990, a to:

- snížit emise skleníkových plynů o 20 % do roku 2020;
- snížit emise skleníkových plynů minimálně o 40 % do roku 2030;
- snížit emise skleníkových plynů o 80–95 % do roku 2050.

ČR v rámci mechanismu vedoucího ke splnění klimatických závazků podle nařízení Evropského parlamentu a Rady (EU) 2018/1999 sestavila Vnitrostátní plán České republiky v oblasti energetiky a klimatu (Ministerstvo průmyslu a obchodu ČR, 2019). Dokument, který byl 13. 1. 2020 schválen vládou, přebírá a potvrzuje závazky stanovené Politikou ochrany klimatu v ČR.

3.7. Význam budov pro mitigaci změny klimatu

Budovy představují významnou oblast produkce skleníkových plynů. Speciální kapitolu jim věnoval i report IPCC (Lucon *et al.*, 2014). Podle údajů Evropské komise tvoří v EU emise skleníkových plynů související s budovami 34 % (European Commission, 2019).

Úsporná opatření na budovách jsou jednou ze šesti hlavních oblastí specificky uvedených v Zelené dohodě pro Evropu (Evropská komise, 2021). Problém změny klimatu vyzdvihují i řady odborníků ze stavebnictví, vznikají i různé petice upozorňující na problém, například, Graz Declaration for Climate Protection in the Built Environment (*Graz Declaration for Climate Protection in the Built Environment*, 2019), v ČR Deklarace udržitelnosti od Architects for Future (Centrum pasivního domu, 2020). Opatření na fondu budov mají významnou roli i v mitigačních strategiích měst a obcí, například v rámci Paktu starostů a primátorů (Covenant of Mayors, 2021).

3.7.1. Původ emisí skleníkových plynů v budovách

V současných budovách je většinovým zdrojem emisí skleníkových plynů výroba energie pro zajištění jejich provozu – výroba tepla na zajištění vytápění, větrání a úpravu vzduchu, ohřev teplé vody, výroba chladu a spotřeba chladiv, spotřeba elektrické energie na osvětlení a pomocné energie. Významná je i spotřeba energie domácích spotřebičů. Dalšími zdroji emisí skleníkových plynů jsou emise nepřímo vyvolané provozem budov, například s externí výrobou a dopravou energie (především elektřiny a tepla), s dodávkou paliv do budovy (například emise spojené s výstavbou a provozem plynovodů, ale i spojené s výrobou paliv z obnovitelných zdrojů), dále se jedná o emise způsobené dodávkou vody či zpracováním tekutých i pevných odpadů.

Další kategorií, která nabývá na významu se zvyšující se energetickou efektivitou budov, jsou takzvané svázané emise skleníkových plynů. Do této kategorie spadají emise skleníkových plynů vyprodukované nepřímo při získávání surovin, výrobě, dopravě a zabudování stavebních materiálů do budov a emise spojené s údržbou, obnovou konstrukcí a odstraňováním staveb po skončení jejich životnosti (Lupíšek *et al.*, 2016; Volf *et al.*, 2018; Röck *et al.*, 2020).

3.7.2. Sledování produkce emisí skleníkových plynů v budovách

Produkci skleníkových plynů je možné poměrně přesně monitorovat u stávajících budov v provozu na základě soupisu reálných spotřeb energií a paliv, které mají na celkových emisích skleníkových plynů většinový podíl. U plánovaných novostaveb se produkce skleníkových plynů modeluje.

Monitorované nebo vypočtené spotřeby energií a paliv se následně přenásobují příslušnými celkovými emisními faktory skleníkových plynů. V závislosti na použité metodice výpočtu se celkové emisní faktory mohou skládat z dílčích emisních faktorů – například u plynu lze uvažovat buď pouze přímé emise, které vzniknou při spálení jednotkového množství plynu, ale lze připočítávat i emise související s těžbou a distribucí zemního plynu a se ztrátami na vedení. U fosilních paliv v emisích skleníkových plynů převažují přímé emise z jejich spalování.

Složitější situace je u elektřiny. U té není možné zcela přesně určit její emisní faktor, protože se jedná o hodnotu dynamicky se měnící v čase, protože závisí na aktuálním energetickém mixu v příslušné rozvodné síti. V případě lokálních distribučních sítí založených na kogeneračních jednotkách může záviset na využití odpadního tepla a konkrétní alokaci emisí mezi vyrobenou elektřinu a teplo.

V případě, že se jedná o reálné odběry, může informace o emisních faktorech za určité uplynulé období poskytnout přímo dodavatel elektřiny (jedná se o tzv. tržní emisní faktor). Zároveň je dnes možné si u některých dodavatelů nasmlouvat odběr elektřiny výhradně z obnovitelných zdrojů (s certifikátem auditora potvrzujícím současnost výroby a spotřeby).

V případě, že není k dispozici informace od dodavatele, nebo se jedná o model budovy ve fázi návrhu, používají se obvykle jednotné národní emisní faktory ze statistik, databází, nebo z platné legislativy. Je možné si ovšem vyžádat informaci o emisním faktoru pro sledované období přímo od konkrétního dodavatele elektrické energie (pak hovoříme o tzv. market-based emisních faktorech).

Situace může být komplikovaná i u odběru dálkového tepla či chladu. Emisní faktory tepla u CZT se mohou velmi lišit v závislosti na konkrétní technologii výroby příslušného dodavatele. I zde nastávají různé kombinace na kogeneračních zdrojích, a i v tomto případě je možné odebírat teplo výhradně z obnovitelných zdrojů. Informace o konkrétních emisních faktorech by měl znát dodavatel energie. Pokud není informace k dispozici, použije se opět národní emisní faktor.

3.8. Role fondu budov v národních klimatických mitigačních strategiích

Byla provedena rešerše dostupných zdrojů s cílem dosažení rámcového přehledu o způsobu, jakým vybrané státy uvažují o plnění klimatických závazků a jaké strategie volí k jejich dosažení a pokud možno identifikovat roli budov v těchto strategiích.

3.8.1. Postup rešerše vědeckých publikací

V roce 2017 byla provedena rešerše odborných publikací pomocí vyhledávání v databázi Web of Science.

Cílem bylo vyhledat publikace, které popisují roli budov nebo stavebnictví jako celku v národních či nadnárodních mitigačních strategiích změny klimatu a zjistit, jak se k této problematice staví evropské státy a velké světové ekonomiky.

Zároveň byly nalezeny publikace, které popisují roli budov v klimatických mitigačních strategiích samosprávních celků menších než národní státy. U těch nebylo cílem vytvořit detailní porovnání, ale pouze získat obecný přehled s příklady států uvnitř federací, provincií, krajů, měst a obcí bez přesnějšího rozlišení.

Do rešerše nebyly zahrnuty publikace, ke kterým se nepodařilo získat plný text.

Klíčová slova

Pro vyhledávání byla použita tato klíčová slova:

- Climate
- Change
- Mitigation
- Plan
- Greenhouse gas emssions
- Building*
- Construction*
- Construction sector
- Nationally determined contributions

V dubnu 2021 pak byla rešerše rozšířena o další aktuální publikace.

3.8.2. Výsledky rešerše

Na úrovni národního fondu budov výzkumníci zkoumali obecný potenciál pro snížení emisí skleníkových plynů a zkoumali různé cesty, jak sladit výkonnost v oblasti emisí skleníkových plynů s klimatickými cíli Pařížské dohody. Xing a kol. v (Xing *et al.*, 2016) zkoumali potenciální příspěvek čínského rezidenčního sektoru ke klimatickým příspěvkům země při různých úrovních uhlíkové daně. Studie vzala rok 2010 jako rok základní a modelovala emise CO_2 pro rok 2020 a pro rok 2030 ve třech scénářích vývoje. Byl zjištěn potenciál dosažení snížení intenzity emisí CO_2 o 60-65 % v rozsahu hypotetických situací odpovídajících cenám emisí uhlíku mezi 44 a 58 USD/t CO_2.

Yu et al. (Yu *et al.*, 2018) modelovali fond budov v Indii s ohledem na vývoj sektoru budov, včetně změn HDP, počtu obyvatel, urbanizace, rozšiřování podlahové plochy, růstu poptávky po energetických službách a volby mezi technologiemi a palivy pro jednotlivé energetické služby. Zjistili, že zavedením široké škály politik energetické účinnosti lze do roku 2050 snížit celkovou spotřebu energie v Indii o 22 % a snížit celkové emise oxidu uhličitého v Indii o 9 %. Jeong (Jeong, 2017) zkoumal čtyři scénáře vývoje sektoru obytných budov v Jižní Koreji v letech 2007 až 2030. Bylo zjištěno, že navzdory očekávané silné poptávce po nové bytové výstavbě existuje v jednom z modelovaných scénářů potenciál pro snížení emisí CO_2 o 12,9 % (ve srovnání s 10,7% nárůstem ve scénáři zachování stávajícího stavu). V Německu v roce 2013 Bürger (Bürger, 2013) analyzoval emise skleníkových plynů národního fondu obytných budov v kontextu využití vývoje stavebních norem, technologií zásobování teplem a potenciálu obnovitelných zdrojů energie. Byly analyzovány tři dlouhodobé scénáře vývoje německého stavebního fondu do roku 2050 a porovnány s emisním rozpočtem, který byl tehdy pro Německo k dispozici. Na základě výsledků autoři vyzvali k urychlenému zavedení dalších důrazných opatření na ochranu klimatu. Práce byla dále rozpracována a popsána v práci Klimaneutraler Gebäudebestand 2050 (Bürger *et al.*, 2016, 2019), která simulovala scénáře snížení emisí skleníkových plynů o -35 %, -50 % a -65 % do roku 2050.

Frischknecht a kol. (Frischknecht *et al.*, 2020) provedli komplexní analýzu uhlíkové stopy švýcarského realitního sektoru. Výsledky ukázaly, že fáze užívání budov představuje pouze dvě třetiny celkových emisí skleníkových plynů v tomto odvětví, zatímco dalších 30 % je způsobeno dodavatelskými řetězci budov, přičemž konstatovali, že relativní význam svázaných skleníkových plynů roste – což bylo také zjištěno šetřením na případových studiích budov (Röck *et al.*, 2020).

Kranzl a kol. (Kranzl *et al.*, 2019) analyzovali scénáře snižování emisí skleníkových plynů z modelu zdola nahoru řízeného politikou, který byl nedávno zaveden pro evropské země v osmi projektech EU a národních projektech (včetně údajů pro Česko), porovnali je mezi sebou pomocí různých ukazatelů a analyzovali, zda by scénáře vedly k dosažení snížení emisí skleníkových plynů v rozmezí 85-95 % do roku 2050. Výsledky ukázaly, že scénáře označené jako ambiciózní pro několik členských států EU dosahují do roku 2050 snížení emisí skleníkových plynů o 56-96 %. Pouze 27 % těchto ambiciózních scénářů však dosahuje snížení emisí nad 85 %.

V České republice jsme (Lupíšek, 2019) dříve zkoumali pět scénářů vývoje českého národního fondu budov modelováním kumulativních emisí CO_2 v období 2015-2030, 2031-2050 a 2051-2075 a porovnávali je se zprávou OSN o emisních mezerách (UNEP, 2016). Vycházeli jsme přitom z dříve vytvořených modelů spotřeby energie českého bytového a nebytového fondu budov, které ve dvou scénářích zohledňovaly i budoucí změny klimatických podmínek v důsledku změny klimatu. Jeho nejprogresivnější scénář předpokládal snížení emisí CO_2 do roku 2075 o 66 %. Žádný z modelovaných scénářů nebyl shledán nedosahoval úrovně požadované v Pařížské dohodě.

Další publikací, která se v nedávné době zabývala emisemi skleníkových plynů v českých budovách, je zpráva Cesty k dekarbonizaci České republiky (Hanzlík *et al.*, 2020). Představuje nákladově optimální cestu dekarbonizace státu (včetně budov) se snížením emisí skleníkových plynů o 31 % do roku 2030 a o 97 % do roku 2050.

3.9. Dostupné definice uhlíkově neutrální budovy

V měřítku jedné budovy se stále více literatury zaměřuje na teorii snižování emisí skleníkových plynů (GHG) z budov. Některé studie se pokusily sladit navrhování budov s průběžnými cíli Pařížské dohody (Chandrakumar *et al.*, 2019; Pálenský and Lupíšek, 2019) a řada prací informuje o pokroku v oblasti budov s nulovými emisemi skleníkových plynů, včetně tzv. klimaticky neutrálních (Musall, 2015), uhlíkově neutrálních (Carruthers and Casavant, 2013) a bezemisních (Haase *et al.*, 2011; Moschetti, Brattebø and Sparrevik, 2019;

Lützkendorf and Frischknecht, 2020) budov. Různé definice a přístupy byly diskutovány na 71. fóru LCA v roce 2019 (Frischknecht *et al.*, 2019) a nedávno je shrnuli Satola a jeho tým (Satola *et al.*, 2021), který analyzoval definice emisní náročnosti budov a jejich příslušné cíle.

3.10. Příklady připravované legislativy regulující provozní a svázané emise skleníkových plynů v budovách

Z evropských zemí jsou v přípravě zavedení legislativy regulující provozní a svázané emise skleníkových plynů v budovách nejdále severské země.

Finská vláda si vytknula ambiciózní cíl dosažení klimatické neutrality již v roce 2035. Budovy chápe jako významný segment, který je potřeba k dosažení tohoto cíle zohlednit. Finsko plánuje v roce 2025 zavedení limitů emisí skleníkových plynů (Kuittinen and Häkkinen, 2020), ve kterých se bude uvažovat celý životní cyklus budovy. Počítat se bude pomocí zjednodušené metodiky LCA. Finská vláda zároveň v nejbližších letech plánuje připravit a volně zpřístupnit národní databázi svázaných emisí skleníkových plynů.

Ještě o krok dále jsou přípravy zavedení limitů v Dánsku. Tamní národní strategie udržitelné výstavby (Ministry of the Interior and Housing, 2021) obsahuje ambiciózní akční plán vedoucí k zavedení limitů na emise skleníkových plynů v životním cyklu budov již v roce 2023. Zavedení předchází testovací období, kdy se provádí hodnocení dobrovolně. Od roku 2023 bude platit povinnost ke všem budovám doložit výpočet GHG pomocí metodiky LCA a pro budovy nad 1 000 m^2 podlahové plochy bude platit limit 12 kg $CO_{2,ekv.}/m^2a$. Na konci roku 2023 dojde k vyhodnocení situace a stanovení zpřísnění limitu, které začne platit od roku 2025 (předpokládá se snížení na 10,5 kg $CO_{2,ekv.}/m^2a$.). V roce 2025 by limity měly začít platit plošně pro všechny budovy. Další revize a další zpřísnění limitu bude následovat periodicky každé dva roky.

4. Analýza fondu budov ČR – podíl na produkci skleníkových plynů ČR a potenciál pro jejich snížení

Tato kapitola je založena na článku *Czech Building Stock: Renovation Wave Scenarios and Potential for CO_2 savings until 2050* (Lupíšek, Trubačík and Holub, 2021), který prezentoval hlavní výsledky studie *Potenciál pro snížení provozních emisí CO_2 z českého fondu budov – Aktualizace červen 2020* (Lupíšek, Trubačík and Holub, 2020). Studie vznikla ve spolupráci Šance pro budovy (ŠPB) a Univerzitního centra energeticky efektivních budov ČVUT v Praze.

4.1. Cíl studie

Studie vycházela z předchozích analýz českého národního fondu budov (NFB), spotřeby energie v něm, a ze scénářů pro energetické úspory. Cílem této studie bylo navázat na předchozí práci a kvantifikovat přibližný potenciál úspor emisí CO_2 z provozu NFB podle aktuálních jednotlivých scénářů modernizace připravených ŠPB v souladu s požadavky dlouhodobé strategie renovace podle článku 2a směrnice o energetické náročnosti budov (EU) 2018/844, a dále vyhodnotit možný příspěvek energeticky úsporných opatření ve fondu budov k národním emisním závazkům s ohledem na aktualizované emisní faktory pro elektřinu, teplo ze systémů dálkového vytápění a budoucí mix plynu v plynovodech.

4.2. Postup

Metody použité v této studii k modelování, výpočtu a vyhodnocení potenciálu úspor provozních emisí CO_2 NFB zahrnovaly následující:

- Definování scénářů rozvoje NFB včetně výchozího stavu, zejména pokud jde o plochu, kvalitu a očekávanou míru modernizace a zvýšení počtu nových staveb;
- Zpracování údajů o spotřebě energie v budovách pro období do roku 2050 (podrobnosti o modelování údajů jsou uvedeny v oddíle níže);
- Definování scénářů podílů zdrojů energie na budoucí spotřebě energie na vytápění, přípravu teplé vody a osvětlení v budovách v souladu se spotřebou uvedenou v energetických průkazech;
- Doplnění odhadů spotřeby energie pro spotřebiče a vaření v sektoru bydlení;
- Určení emisních faktorů CO_2 pro jednotlivá paliva a nosiče energie;
- Výpočet provozních emisí CO_2 NFB pro jednotlivé scénáře modernizace budov;
- Definování scénářů rozvoje fotovoltaických zařízení a variantní modelování emisí CO_2;

- Provedení analýzy citlivosti s ohledem na budoucí snížení emisních faktorů elektřiny z národní sítě, tepla ze systémů dálkového vytápění a plynu z distribuční sítě;
- Výpočet podílu NFB na národních provozních emisích CO_2 a jeho teoretického podílu v roce 2050;
- Hodnocení výsledků s ohledem na národní závazky v oblasti klimatu.

4.2.1. Definice scénářů vývoje českého stavebního fondu a shrnutí odpovídající spotřeby energie

Studie vycházela ze čtyř stavebně-technických scénářů pro modernizaci NFB. Pro každý z nich byly modelovány dílčí scénáře lišící se strukturou zdrojů energie v budovách.

Následující odstavce popisují původ základních údajů o složení NFB, modelování konečné spotřeby energie NFB, čtyři scénáře hloubky a tempa energetické modernizace, projekci podílů energonositelů na konečné spotřebě energie ve čtyřech scénářích a prognózu vývoje fotovoltaiky připojené na budovy a fotovoltaiky integrované do budov (BIPV).

Původ základních údajů o složení NFB

Údaje o skladbě NFB byly získány z několika předchozích zpráv vydaných Šancí pro budovy, zejména ze *Šetření bytového fondu ČR a potenciálu úspor* (Antonín, 2016b), *Šetření nebytového fondu ČR a potenciálu úspor* (Antonín, 2016a), *Strategie modernizace budov* (Holub and Antonín, 2014), její aktualizace z roku 2016 (Šance pro budovy, 2016) a Dlouhodobé strategie obnovy bytového fondu ČR – aktualizace květen 2020 (*Dlouhodobá strategie renovace budov v České republice – aktualizace květen 2020 [Long-term Strategy for Renovation of the Buildings in the Czech Republic – May 2020 update]*, 2020). Data pro tyto zprávy pocházela z různých datových souborů poskytnutých Českým statistickým úřadem, zejména z údajů celostátního sčítání lidu 2011, statistického šetření o budovách s názvem ENERGO 2015 a statistického šetření o budovách s názvem Budovy 1-99 z roku 2018. Základní údaje o skladbě NFB jsou podobné těm, které byly použity v předchozí studii (Lupíšek, 2019).

Modelování konečné spotřeby energie NFB

Základní energetický model NFB byl vytvořen v roce 2016, proto byl rok 2016 výchozím rokem, pro který byly shromážděny statistické údaje. Energetický model se skládá z dílčích modelů bytového a nebytového fondu budov. Ten byl použit pro prognózy ročních celkových konečných spotřeb energie českých bytových a nebytových budov v letech 2016 až 2075; v této studii byly použity datové soubory do roku 2050.

Pro energetické simulace stávajícího fondu obytných budov (Antonín, 2016b) byl použit stochastický energetický model, který vypočítal potřebu energie na vytápění souboru 1 000 simulovaných budov, který byl vytvořen ze vzorků dat budov rozdělených do 78 kategorií podle typologie, velikosti a stáří na základě statistických údajů. Výpočty ve vlastním nástroji (listy a makra MS Excel) se řídily pravidly danými normou EN ISO 13790 a uplatňovaly okrajové podmínky běžně používané při výpočtu průkazů energetické náročnosti podle českých předpisů. Statistické údaje poskytly vstupní údaje pro odhad podílu bytového fondu, který již prošel energetickou modernizací a který byl v roce 2016 odhadnut na 35 %. Zpráva uvádí informace o provedené kalibraci energetického modelu podle dostupných statistických údajů o konečné spotřebě energie fondu budov provedenou porovnáním vypočtené spotřeby energie (52 896 GWh/rok) se statistickými údaji poskytnutými Ministerstvem průmyslu a obchodu ČR (47 798 GWh/rok). Kalibrace modelu na statistické údaje byla provedena snížením uvažované teploty vnitřního vzduchu.

Energetické modelování stávajícího fondu nebytových budov (Antonín, 2016a) bylo založeno na vzorku 100 nebytových budov s podrobnými energetickými simulacemi a na dalším vzorku 20 stávajících budov s podrobnými údaji o skutečné spotřebě energie. Do studie byly zahrnuty typologie budov: kancelářské budovy, administrativní budovy, obchodní budovy, vzdělávací budovy, kulturní budovy, hotely, restaurace, zdravotnická zařízení, sportovní zařízení, skladovací budovy a budovy se smíšeným využitím. Jejich seznam a vzorové fotografie jsou uvedeny ve zprávě (Antonín, 2016a), kde jsou v části 2.1 popsány geometrické charakteristiky vzorku. Oddíl 2.3 popisuje výsledky energetického modelování, které bylo zpracováno v souladu s národní vyhláškou 78/2013 Sb. používanou pro výpočet průkazů energetické náročnosti budov (základní scénář je uveden v grafech a tabulkách označených jako SS a vizualizovaných černou barvou). Výsledné údaje o potřebě energie a konečné spotřebě energie jsou uvedeny od strany 13. Kalibrace energetického modelu byla provedena porovnáním simulovaných spotřeb energie se skutečnými spotřebami energie dvaceti stávajících budov. Na základě těchto srovnání byl odvozen korekční vzorec pro jejich extrapolaci na celý fond nebytových budov. Byl založen na analýze citlivosti, která určila klíčové parametry: poměr plochy k objemu, poměr mezi střední hodnotou U a referenční hodnotou U použitou v metodě výpočtu deklaratorní energetické náročnosti, vnitřní teplotou a celkovou účinností otopného systému.

Simulované spotřeby energie byly extrapolovány na celý český nebytový fond s využitím národních statistických údajů o podílu jednotlivých typů budov na celém fondu budov.

Energetický model zvažuje různé hloubky energetických modernizačních opatření; jejich kombinace je dále popsána v částech věnovaných scénářům.

Obytné budovy statisticky modernizované na nízkoenergetický standard a budovy bez modernizace byly simulovány pomocí stavebních zásahů vedoucích ke snížení potřeby energie na vytápění a zlepšením účinnosti vytápění v důsledku výměny zdrojů tepla. Potenciální úspory z přípravy teplé vody a osvětlení byly simulovány samostatně.

Modelované nebytové budovy, které byly v nižším než současném energetickém standardu, byly simulovány pomocí různých kombinací energeticky úsporných zásahů, jako jsou: částečné zlepšení tepelně technických vlastností obvodových konstrukcí budov; komplexní modernizace obvodových konstrukcí jako celku; výměny zdrojů tepla; instalace systémů mechanického větrání s rekuperací tepla; instalace nových systémů obnovitelných zdrojů energie.

Čtyři scénáře vývoje NFB podle hloubky a tempa energetické modernizace

Pro tuto studii byly definovány čtyři scénáře budoucího vývoje NFB (Tab. 3):

- Základní scénář, který odpovídá současnému stavu politiky bez jakýchkoli zlepšení (business as usual);
- Vládní scénář navržený v Dlouhodobé strategii obnovy podporující obnovu národního bytového a nebytového fondu veřejných a soukromých budov, kterou vydalo Ministerstvo průmyslu a obchodu ČR, jež je zodpovědné za energetickou a stavební politiku (Ministry of Industry and Trade of the Czech Republic, 2020);
- Progresivní scénář (hloubková modernizace NFB);
- Hypotetický scénář (rychlá hloubková modernizace NFB).

Scénáře byly definovány pomocí následujících proměnných:

- Roční míra modernizace: procento fondu budov, které se každoročně modernizuje (podle kategorie budov; Tab. 4).
- Hloubka modernizace: V kontextu studie znamená mělká modernizace, že obálka budovy je modernizována na požadované hodnoty U odpovídající národní normě ČSN 73 0540; střední znamená, že jsou splněny doporučené hodnoty U; hluboká znamená hodnoty U předepsané pro pasivní domy a vybavení budovy mechanickým větráním s rekuperací tepla. Tab. 3 poskytuje další přehled o typických hodnotách U podle hloubky modernizace. Spodní část Tab. 4 ukazuje rozdělení podlahové plochy renovované budovy podle hloubky modernizace. Obr. 10 vizualizuje jednotlivé scénáře.

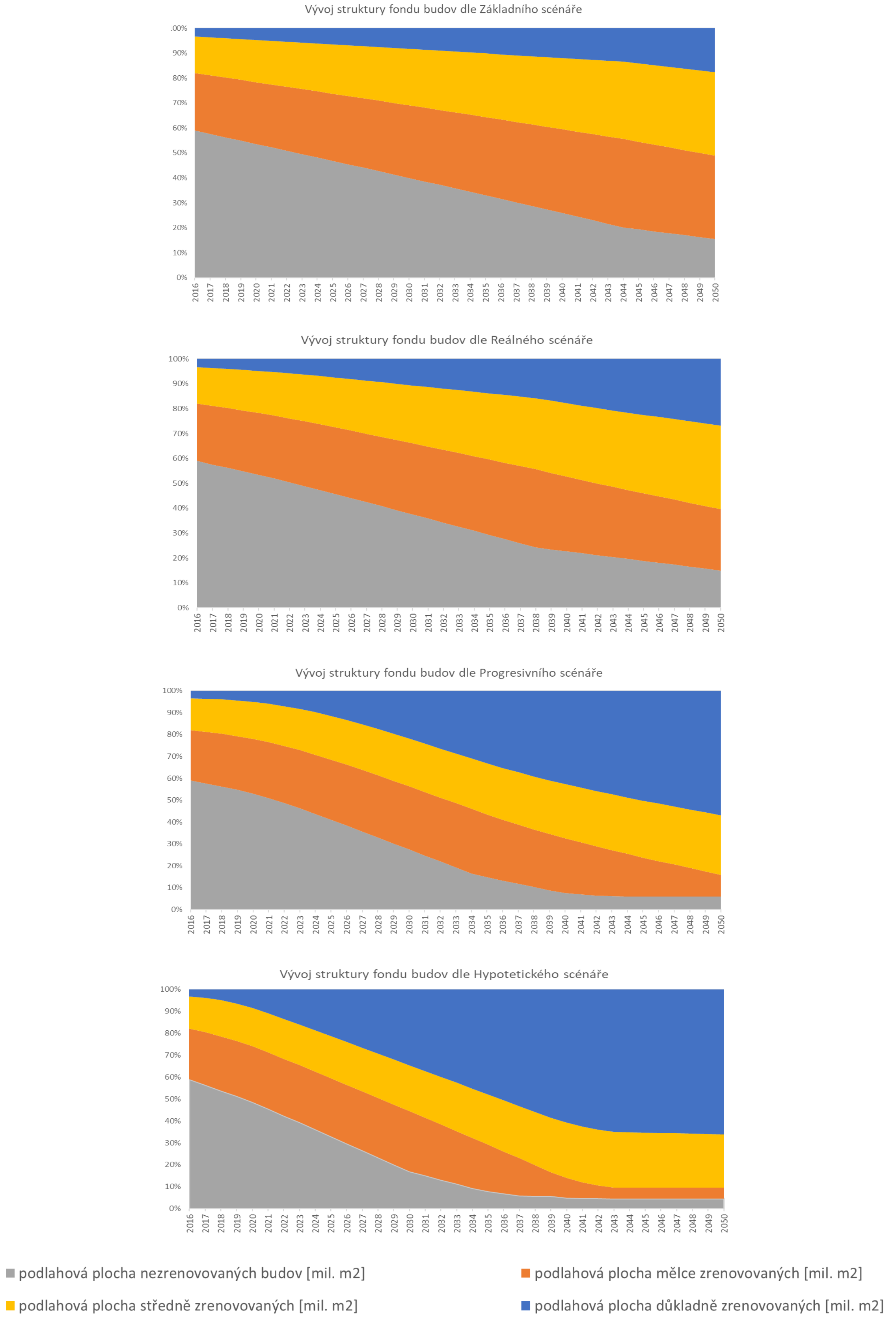
Tab. 3 Hloubka modernizace podle uvažovaných hodnot U hlavních stavebních konstrukcí a větracích systémů pro energetické modelování nebytového fondu.

Typ konstrukce	Hloubky modernizace		
	Mělká	**Mírná**	**Hluboká**
	Tepelná kvalita obálky budovy		
	Typické hodnoty U hlavních skladeb budov ve W/($m^2 \cdot K$)		
Vnější stěny	0,30	lehké 0,25, těžké 0,20	0,15
Střechy	0,24	0,16	0,10
Podlaha pod podkrovím bez tepelné izolace	0,30	0,20	0,12
Podlahové konstrukce nad exteriéry	0,24	0,16	0,12
Podlahové konstrukce nad nevytápěnými podzemními podlažími	0,60	0,40	0,25
Okna	1,50	1,20	0,90
Dveře	1,70	1,20	0,90
	Větrání		
Větrací systém	Přirozené větrání nebo mechanické větrání bez rekuperace tepla	Přirozené větrání nebo mechanické větrání bez rekuperace tepla	Mechanický větrací systém s rekuperací tepla (účinnost $\eta_{H,hr,sys}$ = 60 % podle EN 308)

Tab. 4 Definice čtyř scénářů vývoje NFB

Kategorie budov	**Hloubka modernizace**	**Scénář**			
		Základní	**Vládní**	**Progresivní**	**Hypotetický**
Nová výstavba a demolice: roční nárůst podlahové plochy *					
Rodinné domy		1,11 %	1,11 %	1,11 %	1,11 %
Bytové domy		0,46 %	0,46 %	0,46 %	0,46 %
Nerezidenční budovy		0,96 %	0,96 %	0,96 %	0,96 %
Roční míra modernizace podle kategorií (procento fondu budov, které se ročně modernizuje)					
Rodinné domy		1,40 %	1,40 %	3,00 %	3,00 %
Bytové domy		0,79 %	0,79 %	2,00 %	3,00 %
Nerezidenční budovy		1,40 %	2,00 %	2,50 %	3,00 %
Rozložení podlahové plochy renovovaných budov podle hloubky modernizace a jejich časové rozložení					
Podíly hloubky modernizace podle kategorií budov		Postupný pokles, stabilní po celé období **	Lineární nárůst od výchozího stavu do roku 2025, poté stabilní.	Lineární nárůst od výchozího stavu do roku 2025, poté stabilní.	Hypotetický skok v roce 2020 a poté stabilní stav
Rodinné domy Bytové domy	**Mělká**	35 %	20 %	5 %	5 %
	Mírná	38 %	40 %	10 %	10 %
	Hluboká	27 %	40 %	85 %	85 %
Rodinné domy Bytové domy	**Mělká**	31 %	20 %	5 %	5 %
	Mírná	50 %	40 %	10 %	10 %
	Hluboká	19 %	40 %	85 %	85 %
Rodinné domy	**Mělká**	27 %	20 %	5 %	5 %
	Mírná	44 %	40 %	10 %	10 %
	Hluboká	30 %	40 %	85 %	85 %

* Uvažovaná míra demolice: rodinné domy 0,2 %, vícegenerační domy 0,1 %, nebytové budovy 0,2 %. ** Výchozí podíly hloubek modernizace z databáze ENEX, která shromažďuje údaje z energetických certifikátů uvedených pro účely "větší renovace stávající budovy", převzato z (Ministry of Industry and Trade of the Czech Republic, 2020).



Obr. 10: Modelované podíly nerenovovaných, mělce renovovaných, středně renovovaných a hluboce renovovaných budov v celém NFB (podle podlahové plochy budov).

Z energetického modelu byla získána roční konečná spotřeba energie pro bytové a nebytové budovy v letech 2016 až 2050. Tab. 5 uvádí vybrané údaje.

Tab. 5 Zjednodušený přehled roční spotřeby konečné energie v PJ získaný z energetického modelu, který byl použit pro modelování emisí oxidu uhličitého v NFB.

Scénář	2016	2030	2040	2050
Rezidenční budovy				
Základní	253	234	219	204
Vládní		232	214	196
Progresivní		206	154	126
Hypotetický		179	126	115
Nerezidenční budovy				
Základní	125	117	109	102
Vládní		113	102	93
Progresivní		107	94	86
Hypotetický		98	85	83

Protože energetický model použitý pro obytné budovy nezahrnoval spotřebu energie na vaření a domácí spotřebiče, byly tyto spotřebiče nakonec doplněny v ročním množství 15,5 PJ pro domácí spotřebiče (v elektřině) a 15,0 PJ pro vaření (stejný podíl elektřiny a zemního plynu). Tyto hodnoty byly uvažovány pro každý modelovaný rok konstantní.

Projekce podílů nosičů energie na konečné spotřebě energie ve čtyřech scénářích

Projekce podílů nosičů energie byly stanoveny zvlášť pro bytový a nebytový fond budov pro roky 2016 a 2050 a hodnoty pro mezilehlé roky byly lineárně interpolovány. Základní hodnoty pro rok 2016 byly stanoveny na základě analýzy výše uvedených zdrojů Českého statistického úřadu. Hodnoty pro rok 2050 byly definovány na základě národních energetických závazků analýzou národních strategických dokumentů, které v nedávné době zveřejnilo Ministerstvo průmyslu a obchodu ČR, zejména *Národního energetického a klimatického plánu České republiky* (Ministry of Industry and Trade, 2020). Definice podílu obnovitelných zdrojů energie vycházela ze zpráv České komory obnovitelných zdrojů energie zabývajících se potenciálem obnovitelných zdrojů energie v budovách a ze zprávy Česko na cestě k uhlíkové neutralitě (Komora obnovitelných zdrojů energie, 2020). Uvažované podíly energetických nosičů a zdrojů jsou shrnuty v Tab. 6. Fotovoltaikou se zabývá následující oddíl.

Tab. 6 Uvažované podíly energetických nosičů a zdrojů na konečné spotřebě energie ve čtyřech scénářích.

Scénář		Základní	Vládní	Progresivní	Hypotetický
Nosič/zdroj energie	**2016**	**2050**	**2050**	**2050**	**2050**
		Rezidenční budovy			
Topné oleje	0 %	0 %	0 %	0 %	0 %
Zemní plyn	30 %	25 %	26 %	23 %	22 %
Uhlí	12 %	10 %	3 %	0 %	0 %
Biomasa (bez pelet)	20 %	25 %	20 %	15 %	12 %
Pelety	0,3 %	4 %	9 %	14 %	16 %
Dálkové vytápění	17 %	16 %	16 %	15 %	15 %
Elektřina	19 %	10 %	11 %	8 %	8 %
Solární kolektory	0,3 %	2 %	4 %	6 %	7 %
Tepelná čerpadla	1 %	9 %	12 %	19 %	21 %
		Nerezidenční budovy			
Plynová kogenerace	2 %	2 %	2 %	2 %	2 %
Zemní plyn	27 %	26 %	23 %	22 %	22 %
Uhlí	0,2 %	0,2 %	0 %	0 %	0 %
Biomasa (bez pelet)	0 %	0 %	0 %	0 %	0 %
Pelety	0,3 %	4 %	8 %	8 %	9 %
Dálkové vytápění	29 %	28 %	25 %	25 %	25 %
Elektřina	42 %	39 %	36 %	36 %	35 %
Solární kolektory	0,2 %	2 %	4 %	4 %	4 %
Tepelná čerpadla	0 %	0,2 %	3 %	3 %	3 %

Prognóza vývoje BIPV

Scénáře výroby elektřiny z BIPV se v rámci scénářů liší. Základním rozdílem je hloubka modernizace: čím hlubší je modernizace, tím větší je předpoklad preference komplexnějších projektů, a tedy i instalace fotovoltaického systému. Scénáře byly spárovány se scénáři z dokumentu Potenciál využití obnovitelných zdrojů energie v budovách (2018) poskytnutého Českou komorou obnovitelných zdrojů energie, který zkoumal technický potenciál pro BIPV. Vycházelo se z optimální orientace a sklonu, což je v Česku jižně orientovaná plocha se sklonem 35°. Pro instalaci BIPV byly uvažovány plochy střech, které mají nižší energetický výnos než 20 %, a stěn nižší než 40 % oproti optimální poloze, přičemž za maximální využitelnou plochu na střechách pro BIPV je považováno 40 % a u stěn orientovaných na jih pouze 20 % plochy. Rovněž se předpokládalo, že 30 % budov není pro instalaci fotovoltaických panelů vůbec vhodných z důvodu zastínění vegetací, jinými budovami nebo z důvodu zákonných omezení či památkové ochrany. Uvažovaná účinnost fotovoltaických panelů byla 18 %. Výsledná výroba elektřiny z BIPV je uvedena v Tab. 7.

Tab. 7 Uvažované roční množství výroby elektřiny v GWh z fotovoltaických zařízení připojených k budovám a integrovaných do budov. Hodnoty pro mezilehlé roky byly lineárně interpolovány

Sektor	Scénář	2016	2030	2040	2050
Rezidenční budovy	**Základní a vládní**	262	2 944	4 710	6 477
	Progresivní	262	5 561	8 995	12 430
	Hypotetický	262	5 414	9 707	14 000
Nerezidenční budovy	**Základní a vládní**	140	1 560	2 490	3 420
	Progresivní	140	2 940	4 755	6 570
	Hypotetický	140	3 129	5 265	7 400
Celý fond budov	**Základní a vládní**	402	4 504	7 200	9 897
	Progresivní	402	8 501	13 750	19 000
	Hypotetický	402	8 543	14 971	21 400

4.2.2. Výpočty emisí CO_2 ve scénářích

Postup výpočtu množství emisí CO_2 zahrnoval tyto kroky:

- Na základě vstupních ročních datových souborů pro celkovou spotřebu energie pro bytový a nebytový fond ve čtyřech scénářích (údaje pro roky 2016, 2030, 2040 a 2050 jsou uvedeny v Tab. 5);
- Rozdělení celkové spotřeby energie na jednotlivé nosiče energie a zdroje energie podle Tab. 6;
- Rozdělení výroby elektřiny z BIPV pro každý rok podle Tab. 7;
- Vynásobení spotřeby energie odpovídajícím emisním faktorem (níže);
- Součet výsledných emisí pro každý rok ve čtyřech scénářích.

4.2.3. Předpoklady o emisních faktorech

Emisní faktory CO_2 pro paliva byly získány z Národní inventarizační zprávy (Krtková, Müllerová and Saarikivi, 2020; Ministertsvo životního prostředí, 2020). Pro emisní faktor elektřiny ze sítě nebylo k dispozici žádné jednotné oficiální číslo. Na základě analýzy dostupných zdrojů (European Environmental Agency, 2017; Koffi *et al.*, 2017; IEA, 2019) a konzultací se zástupci Ministerstva životního prostředí jsme stanovili emisní faktor na 0,6 t CO_2/MWh.

Rozhodování o jednotném emisním faktoru pro teplo ze systémů dálkového vytápění je obtížné, protože emisní faktory jsou místně specifické a použitá paliva závisí také na účinnosti zdroje tepla, ztrátách v systému a v případě kogenerace na rozdělení vyprodukovaných emisí mezi vyrobené (a někdy i zmařené) teplo a elektřinu. Byly zohledněny různé zdroje relevantních informací (Euroheat, 2006; Ecoheat4Citites, 2012; Spitz and Harnych, 2017; Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2019); pro teplo ze systémů CZT byla zvolena hodnota 0,3 t CO_2/MWh.

Emise z plynových kogeneračních jednotek byly přibližně vyjádřeny snížením emisního faktoru spalování zemního plynu na polovinu. Při výpočtech emisí z tepelných čerpadel byl uvažován průměrný koeficient účinnosti 3,0 a jako nosič energie elektřina ze sítě (výsledný emisní faktor byl tedy třetinový oproti emisnímu faktoru elektřiny).

Výpočet předpokládal, že elektřina vyrobená na místě z BIPV ušetří elektřinu, která by jinak musela být vyrobena v centralizovaných zdrojích dodávajících energii do národní elektrické sítě. Proto byla množství energie vyrobená z fotovoltaiky vynásobena emisním faktorem pro elektřinu ze sítě a odečtena od celkových hodnot za každý rok.

U biomasy jsme v souladu s českými metodami energetického auditu předpokládali udržitelné hospodaření v lesích a zjednodušení vedoucí k nulovému emisnímu faktoru. Podobně byl nulový emisní faktor použit pro teplo ze solárních termických kolektorů (bez zohlednění svázaných dopadů a zanedbání potřebné pomocné energie).

Emisní faktory CO_2 použité při výpočtu jsou shrnuty v Tab. 8.

Tab. 8 Emisní faktory CO_2 použité ve výpočtech v tunách CO_2/MWh

Palivo nebo energonositel	Uvažovaný emisní faktor (t CO_2/MWh)
Uhlí	0,35
Topné oleje	0,26
Zemní plyn	0,20
Biomasa	0,00
Teplo ze solárních kolektorů	0,00
Elektřina ze sítě	0,60
Elektřina vyrobená na místě z BIPV	(−)0,60
Teplo ze systému dálkového vytápění	0,30
Energie z kombinované výroby elektřiny a tepla z plynu	0,10
Teplo z tepelných čerpadel	0,20

Vzhledem k nejistotám ohledně emisních faktorů a předpokládanému budoucímu snížení některých z nich s očekávanou dekarbonizací české energetiky byla provedena citlivostní analýza, jak je popsáno níže.

4.2.4. Analýza citlivosti zohledňující budoucí snížení emisních faktorů elektřiny ze sítě, tepla ze systémů dálkového vytápění a plynu z distribuční soustavy

Vzhledem k nejistotám ohledně emisních faktorů pro elektřinu, dálkové teplo a možný budoucí vývoj skladby zdrojů plynu byla provedena analýza citlivosti pro rok 2050. Analýza citlivosti byla provedena jak bez zohlednění BIPV, tak s ním. Neřešili jsme technický nebo právní potenciál emisních faktorů – citlivostní analýza byla provedena pouze za účelem ukázat scénáře "co kdyby".

Účinky potenciálního snížení emisních faktorů byly zkoumány samostatně. U elektřiny ze sítě bylo použito snížení emisních faktorů o 67 % a 33 % z původní hodnoty 0,6 na 0,4 a 0,2 t CO_2/MWh. To zohledňuje možnou budoucí dekarbonizaci elektrické sítě (na úrovni energetických společností). U dálkového vytápění bylo použito snížení emisních faktorů o 75 % a 50 %, tj. z výchozí hodnoty 0,3 na hodnoty 0,225 a 0,15 t CO_2/MWh. To zohledňuje možnou budoucí výměnu uhelných zdrojů za plyn nebo biomasu. Pro plyn bylo použito snížení emisního faktoru na 90 % a 80 %, tj. z původní hodnoty 0,2 na hodnoty 0,18 a 0,16 t CO_2/MWh. To odráží možné budoucí vtláčení bioplynu do distribuční soustavy nebo syngasu vyráběného pomocí přebytečné nízkoemisní elektřiny z obnovitelných zdrojů nebo jádra. Ve druhém kroku bylo toto snížení emisních faktorů přiřazeno dvěma variantním scénářům snížení emisních faktorů, jak je popsáno v Tab. 9.

Tab. 9 Variantní scénáře emisních faktorů CO_2 (EF) použité v analýze citlivosti pro elektřinu, teplo ze systémů dálkového vytápění a plyn ze systémů distribuce plynu pro rok 2050 v metrických tunách CO_2/MWh.

Palivo nebo energonositel	Emisní faktory pro variantní scénáře pro rok 2050 (t CO_2/MWh)		
	EF1 (výchozí stav)	**EF2**	**EF3**
Elektřina ze sítě	0.600	0.400	0.200
Teplo ze systému dálkového vytápění	0.300	0.225	0.150
Plyn z distribuční soustavy	0.200	0.180	0.160

4.3. Výsledky

4.3.1. Výsledky vypočtených emisí CO_2 ve scénářích

Výsledné emise podle scénářů jsou uvedeny v následujících tabulkách. Tab. 10 uvádí emise dosažitelné energeticky účinnou modernizací budov pro každý jednotlivý scénář, tj. zlepšením kvality obvodových plášťů budov, nahrazením zdrojů účinnějšími, použitím účinných řídicích systémů a použitím mechanického větrání s rekuperací tepla, avšak bez instalace fotovoltaických systémů. Tab. 11 zahrnuje také BIPV. Pro zjednodušení nejsou v tabulkách uvedeny hodnoty pro jednotlivé roky mezi rokem 2016 (který byl základním rokem energetického modelu) a rokem 2050, ale pouze pro roky 2016, 2030, 2040 a 2050.

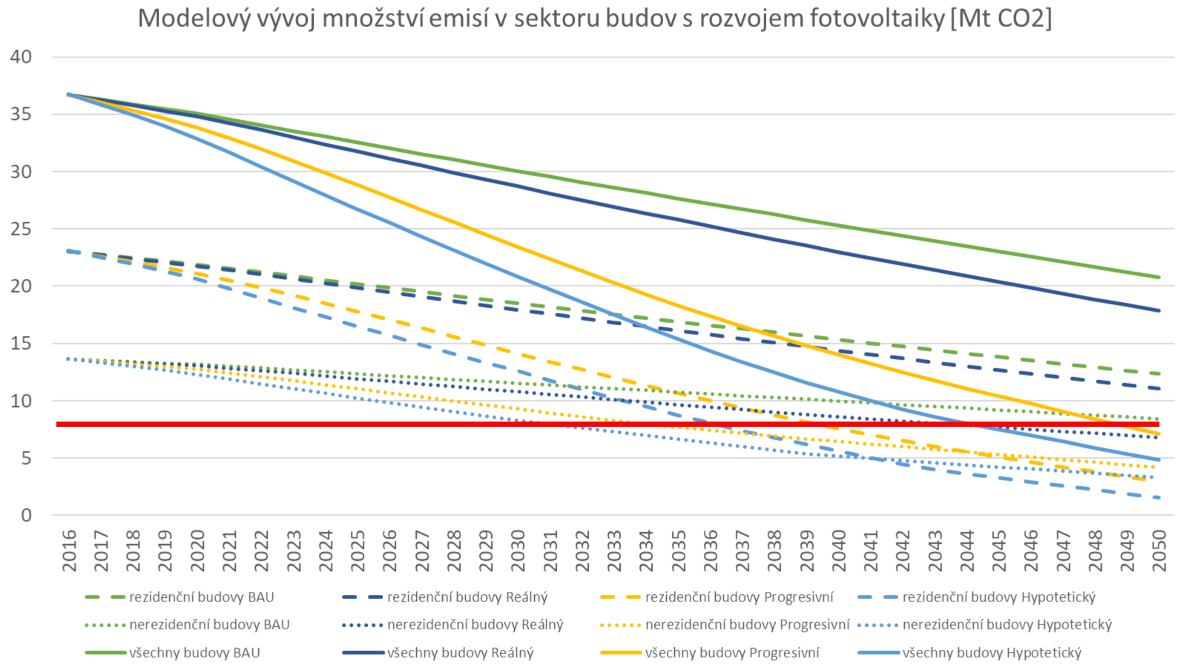
Tab. 10 Výsledné emise CO_2 z provozu českého fondu budov pro jednotlivé scénáře bez zohlednění BIPV. Hodnoty jsou uvedeny v Mt CO_2/rok.

Segment	Scénář	Rok			
		2016	2030	2040	2050
Rezidenční	Základní	23,2	20,3	18,2	16,2
	Vládní		19,7	17,2	14,9
	Progresivní		17,5	13,0	10,4
	Hypotetický		15,8	11,4	9,9
Nerezidenční	Základní	13,7	12,5	11,5	10,5
	Vládní		11,7	10,1	8,9
	Progresivní		11,1	9,3	8,1
	Hypotetický		10,1	8,3	7,7
Celý fond budov	Základní	36,9	32,8	29,6	26,7
	Vládní		31,4	27,3	23,8
	Progresivní		28,5	22,3	18,5
	Hypotetický		26,0	19,8	17,7

Tab. 11 Výsledné emise CO_2 z provozu českého stavebního fondu pro jednotlivé scénáře zohledňující výrobu elektřiny z BIPV na místě. Hodnoty jsou uvedeny v Mt CO_2/rok.

Segment	Scénář	Rok			
		2016	2030	2040	2050
Rezidenční	Základní	23,1	18,5	15,3	12,3
	Vládní		17,9	14,4	11,0
	Progresivní		14,1	7,6	2,9
	Hypotetický		12,6	5,6	1,5
Nebytové prostory	Základní	13,6	11,5	10,0	8,4
	Vládní		10,8	8,6	6,8
	Progresivní		9,3	6,5	4,2
	Hypotetický		8,3	5,2	3,3
Celý fond budov	Základní	36,7	30,0	25,3	20,8
	Vládní		28,7	23,0	17,8
	Progresivní		23,4	14,0	7,1
	Hypotetický		20,8	10,8	4,8

Výsledky výpočtu ukazují potenciál snížení provozních emisí CO_2 NFB do roku 2050 bez zohlednění fotovoltaiky v rozmezí přibližně 27,6 % v základním scénáři a 52,0 % v hypotetickém scénáři ve srovnání s rokem 2016. Zahrnutí BIPV umožňuje celkové snížení emisí CO_2 v rozmezí od 43,6 % do 86,9 %. Výsledky jsou na Obr. 11.



Obr. 11 Modelovaný vývoj množství provozních emisí CO_2 českého stavebního fondu včetně zohlednění BIPV (uvažovány konstantní emisní faktory v Mt CO_2). Přerušované čáry představují nebytový fond budov, čárkované čáry představují bytový fond budov a plné čáry znázorňují celkové hodnoty pro celý NFB. Červená čára představuje emisní cíl pro rok 2050 pro celou NFB.

4.3.2. Výsledky analýz citlivosti podle scénáře

V následujících tabulkách jsou uvedeny výsledky analýzy citlivosti hodnot provozních emisí CO_2 v roce 2050. Ukazují citlivost na emisní faktory elektřiny ze sítě, z distribuce, resp. Z dálkového vytápění. Citlivost na kombinace emisních faktorů podle kombinovaných variant EF1-EF3 je uvedena v Tab. 15.

Tab. 12 Citlivost výsledných emisí CO_2 z provozu NFB na hodnotu emisního faktoru elektřiny v roce 2050 pro jednotlivé scénáře. Hodnoty jsou uvedeny v Mt CO_2/rok.

Elektřina		**Bez BIPV**			**S BIPV**		
Emisní faktor (t CO_2/MWh)		**0,6**	**0,4**	**0,2**	**0,6**	**0,4**	**0,2**
Rezidenční	**Základní**	16,2	13,4	10,6	12,3	10,8	9,4
	Vládní	14,9	12,0	9,2	11,0	9,5	7,9
	Progresivní	10,4	8,1	5,9	2,9	3,2	3,4
	Hypotetický	9,9	7,7	5,5	1,5	2,1	2,7
Nerezidenční	**Základní**	10,5	8,3	6,1	8,4	6,9	5,4
	Vládní	8,9	7,0	5,1	6,8	5,6	4,4
	Progresivní	8,1	6,4	4,6	4,2	3,8	3,3
	Hypotetický	7,7	6,1	4,4	3,3	3,1	2,9
Celý fond budov	**Základní**	26,7	21,7	16,7	20,8	17,8	14,8
	Vládní	23,8	19,0	14,2	17,8	15,1	12,3
	Progresivní	18,5	14,5	10,5	7,1	6,9	6,7
	Hypotetický	17,7	13,8	9,9	4,8	5,2	5,6

Tab. 13. Citlivost výsledných emisí CO_2 z provozu NFB na hodnotu emisního faktoru plynu z distribuční soustavy v roce 2050 pro jednotlivé scénáře. Hodnoty jsou uvedeny v Mt CO_2/rok.

Plyn		**Bez BIPV**			**S BIPV**		
Emisní faktor plynu (t CO_2/MWh)		**0,20**	**0,18**	**0,16**	**0,20**	**0,18**	**0,16**
Rezidenční	**Základní**	16,2	15,9	15,6	12,3	12,0	11,7
	Vládní	14,9	14,6	14,3	11,0	10,7	10,4
	Progresivní	10,4	10,2	10,0	2,9	2,7	2,5
	Hypotetický	9,9	9,8	9,6	1,5	1,4	1,2
Nerezidenční	**Základní**	10,5	10,3	10,2	8,4	8,3	8,1
	Vládní	8,9	8,8	8,6	6,8	6,7	6,6
	Progresivní	8,1	8,0	7,9	4,2	4,1	4,0
	Hypotetický	7,7	7,6	7,5	3,3	3,2	3,1
Celý fond budov	**Základní**	26,7	26,2	25,8	20,8	20,3	19,8
	Vládní	23,8	23,3	22,9	17,8	17,4	17,0
	Progresivní	18,5	18,2	17,9	7,1	6,8	6,5
	Hypotetický	17,7	17,4	17,1	4,8	4,6	4,3

Tab. 14 Citlivost výsledných emisí CO_2 z provozu NFB na hodnotu emisního faktoru tepla ze systémů dálkového vytápění v roce 2050 pro jednotlivé scénáře. Hodnoty jsou uvedeny v Mt CO_2/rok.

Dálkové vytápění			**Bez BIPV**			**S BIPV**	
Emisní faktor tepla ze systému dálkového vytápění (t CO_2/MWh)		**0,300**	**0,225**	**0,150**	**0,300**	**0,225**	**0,150**
Rezidenční	**Základní**	16,2	15,6	14,9	12,3	11,7	11,0
	Vládní	14,9	14,3	13,6	11,0	10,4	9,8
	Progresivní	10,4	10,0	9,6	2,9	2,6	2,2
	Hypotetický	9,9	9,6	9,2	1,5	1,2	0,8
Nerezidenční	**Základní**	10,5	9,9	9,3	8,4	7,8	7,2
	Vládní	8,9	8,4	7,9	6,8	6,3	5,9
	Progresivní	8,1	7,7	7,2	4,2	3,7	3,3
	Hypotetický	7,7	7,3	6,9	3,3	2,9	2,4
Celý fond budov	**Základní**	26,7	25,4	24,2	20,8	19,5	18,3
	Vládní	23,8	22,7	21,6	17,8	16,7	15,6
	Progresivní	18,5	17,7	16,9	7,1	6,3	5,5
	Hypotetický	17,7	16,9	16,1	4,8	4,1	3,3

Tab. 15. Citlivost výsledných emisí CO_2 z provozu NFB na kombinaci zlepšených emisních faktorů v roce 2050 pro jednotlivé scénáře. Hodnoty jsou uvedeny v Mt CO_2/rok.

Kombinace		Bez BIPV			S BIPV		
Scénář emisí		**EF1**	**EF2**	**EF3**	**EF1**	**EF2**	**EF3**
Rezidenční	**Základní**	16,2	12,5	8,7	12,3	9,9	7,4
	Vládní	14,9	11,1	7,3	11,0	8,5	6,0
	Progresivní	10,4	7,5	4,7	2,9	2,6	2,2
	Hypotetický	9,9	7,2	4,4	1,5	1,6	1,6
Nerezidenční	**Základní**	10,5	7,5	4,6	8,4	6,2	3,9
	Vládní	8,9	6,4	3,9	6,8	5,0	3,2
	Progresivní	8,1	5,8	3,5	4,2	3,2	2,2
	Hypotetický	7,7	5,6	3,4	3,3	2,6	1,9
Celý fond budov	**Základní**	26,7	20,0	13,3	20,8	16,0	11,3
	Vládní	23,8	17,5	11,1	17,8	13,5	9,1
	Progresivní	18,5	13,4	8,2	7,1	5,8	4,4
	Hypotetický	17,7	12,7	7,8	4,8	4,2	3,5

5. Vyhodnocení potenciálu úspor skleníkových plynů na provozu fondu budov ČR z pohledu národních závazků v oblasti ochrany klimatu

5.1. Východiska

Abychom bylo možné vyhodnotit výsledky studie s ohledem na národní klimatické závazky, bylo nutné shrnout vstupní údaje týkající se národních klimatických závazků. Česká republika se ve své Politice ochrany klimatu zavázala snížit emise skleníkových plynů nejméně o 80 % oproti roku 1990 (Ministerstvo životního prostředí České republiky, 2017). Nedávno česká vláda podpořila uhlíkovou neutralitu EU jako celku do roku 2050 a vyjádřila ochotu zavázat se k národnímu snížení emisí o 95 % do roku 2050, ale toto prohlášení zatím nebylo zhmotněno do žádné národní politiky. Podle *Národního energeticko-klimatického plánu České republiky* (Ministry of Industry and Trade, 2020) vyprodukovala Česká republika v roce 1990 celkem 194,35 Mt $CO_{2,ekv.}$ (bez zohlednění LULUCF a odpadů). Do roku 2016 se tyto emise snížily na 124,02 Mt $CO_{2,ekv}$. Splnění závazku si vyžádá snížení ročních emisí na 38,87 Mt $CO_{2,ekv}$.

V této studii nebyly k dispozici úplné lokalizované emisní faktory pro potenciál globálního oteplování, proto byly uvažovány pouze emise oxidu uhličitého. Přehled produkce skleníkových plynů podle jednotlivých plynů poskytuje Národní inventarizační zpráva České republiky z roku 2020 (Krtková, Müllerová and Saarikivi, 2020). Pro emise CO_2 v ČR v roce 1990 uvádí hodnotu 164,2 Mt. Uvažujeme-li teoreticky rovnoměrné rozdělení národního závazku mezi sledované skleníkové plyny a sektory (při použití metody rovnoměrné kontrakce), znamená závazek 80% snížení produkce CO_2 do roku 2050 o maximálně 32,8 Mt. V roce 2016 činila tato produkce 106,6 Mt CO_2, do roku 2050 je tedy nutné snížit roční produkci emisí ČR o dalších 73,8 Mt CO_2.

Výsledky této studie ukázaly, že fond budov vyprodukoval v roce 2016 celkem 36,9 Mt CO_2, což znamená, že provoz fondu budov se na celkových národních emisích podílel přibližně 34,6 %. Maximální cílová hodnota potřebná ke splnění přiměřeného národního emisního závazku přiděleného fondu budov je 11,4 Mt CO_2 pro rok 2050.

Pro rok 1990 lze zpětně odhadnout emise z fondu budov na 67,25 Mt CO_2 (tento odhad je však velmi nepřesný; emise na počátku 90. let prudce poklesly zejména v důsledku útlumu těžkého průmyslu a hospodářské restrukturalizace).

5.2. Vyhodnocení

Výsledky výpočtů ukázaly, že modelovaný fond budov vyprodukoval v roce 2016 celkem 36,9 Mt CO_2, přičemž 23,3 Mt CO_2 pocházelo z rezidenčních budov a 13,7 Mt CO_2 z nerezidenčních budov. Celková podlahová plocha budov v roce 2016 činila 599,49 mil. m^2 a průměrná emisní intenzita pro celý fond budov byla 61,6 kg CO_2/m^2rok.

Ve stejném roce 2016 činily národní emise 106,6 Mt CO_2, což znamená, že podíl provozu fondu budov na celkových národních emisích činil přibližně 34,7 %. Podíl rezidenčních budov na národních emisích činil přibližně 21,9 % a podíl nerezidenčních budov 12,9 %.

Pokud jde o přesnost poskytnutých výsledků, výpočty emisí základního scénáře byly založeny na údajích o spotřebě energie z energetického modelu, který byl kalibrován na dostupné národní statistiky a na emisních faktorech uvedených v Tab. 8. Vstupní hodnoty týkající se paliv byly tedy co nejpřesnější; na druhou stranu jsou zdrojem nejistot emisní faktory elektřiny ze sítě a emisní faktor tepla ze systémů CZT (oba byly zastoupeny pouze jedním číslem).

Národní závazek přepočtený na emise CO_2 v roce 2050 představuje celkovou produkci emisí 32,8 Mt CO_2. Pokud budeme pro zjednodušení předpokládat rovnoměrné rozdělení odpovědnosti za snižování emisí mezi sektory české ekonomiky, můžeme uvažovat konstantní podíl národních emisí pro fond budov. To by znamenalo, že cílové maximální roční emise CO_2 z provozu fondu budov v roce 2050 by činily 11,4 Mt CO_2. Očekávaná podlahová plocha budov v roce 2050 byla odhadnuta na 741,02 mil. m^2, takže cílová emisní náročnost fondu budov pro splnění národního závazku byla vypočtena na 15,4 kg CO_2/m^2rok.

Srovnání hodnot emisí v jednotlivých scénářích s maximální cílovou hodnotou potřebnou ke splnění národního emisního závazku ve výši 11,4 Mt CO_2 ukázalo, že závazek lze splnit pouze realizací progresivního scénáře alespoň v případě modernizace budov v kombinaci s rozvojem fotovoltaiky.

V hypotetickém scénáři by byl cíl splněn již v roce 2040 a v roce 2050 by se blížil závazku plně dekarbonizovat český stavební fond. Základní scénář nevede k dostatečnému snížení: dosahuje téměř dvojnásobku hodnoty cíle pro rok 2050. Vládní scénář pak překračuje cílovou hodnotu o 56 %.

Pro splnění emisního závazku České republiky je nutné do roku 2050 snížit roční národní produkci emisí o 73,8 Mt CO_2. V případě realizace Hypotetického scénáře zohledňujícího fotovoltaiku by se ročně ušetřilo 31,9 Mt CO_2, což by ke snížení na národní úrovni přispělo celkem 43,2 %, tj. vyšším podílem než současné emise z budov na celkových emisích.

Pokud se v hypotetickém scénáři bez rozvoje fotovoltaiky sníží emisní faktor elektřiny ze sítě o 33 % na 0,4 t CO_2/MWh, sníží se emise NFB do roku 2050 o 22,0 % ve srovnání s modelem s konstantním emisním faktorem. V případě snížení o 67 % na 0,2 t CO_2/MWh by pokles činil přibližně 44,0 %. Snížení emisního faktoru tepla ze systémů dálkového vytápění o 25 %, resp. 50 % by snížilo emise o 4,5 %, resp. 9,0 %. Snížení emisního faktoru plynu o 10 %, resp. 20 % by vedlo k poklesu emisí oxidu uhličitého o 1,7 %, resp. 3,4 %. V případě snížení emisních faktorů podle kombinace emisních faktorů EF2 by snížení emisí činilo 28,2 %; EF3 by vedlo ke snížení emisí o 56,5 %.

V případech, kdy je zahrnuta BIPV a odpočet teoreticky přebytečné elektřiny je porovnáván s emisním faktorem elektřiny ze sítě, je situace méně jasná, protože čím vyšší je odečet, tím vyšší je emisní faktor elektřiny a tím rychlejší je rozvoj fotovoltaiky. V praxi to znamená, že s klesajícím emisním faktorem elektřiny budou celkové emise z budov v roce

2050 o něco vyšší ve scénáři nejprogresivnější modernizace, protože tento scénář počítá i s rychlým rozvojem fotovoltaiky, jejíž výroba je exportována do sítě.

V hypotetickém scénáři do roku 2050 lze celkové emise v odvětví stavebnictví snížit až o 90 % oproti roku 2016 díky integraci fotovoltaiky a zohlednění kombinace emisních faktorů EF3.

5.3. Diskuse

5.3.1. Nejistoty

Vzhledem k rozsahu energetického modelu bylo v této studii nutné provést řadu zjednodušení, která nevyhnutelně vedou k nejistotám.

Hlavním zdrojem nejistoty jsou použité emisní faktory. Na rozdíl od předchozí studie z roku 2016 (Lupíšek, 2019) publikované v roce 2019, která vycházela z emisního faktoru elektřiny ze sítě, který vycházel z již zastaralé hodnoty 1,17 kg CO_2/kWh uvedené v tehdy platné vyhlášce pro provádění energetických auditů, zde byl použit emisní faktor bližší statistickým hodnotám pro český energetický mix 0,6 kg CO_2/kWh, což je přibližně polovina staré hodnoty. To vedlo k výrazné korekci směrem ke snížení výsledných emisí CO_2. V budoucích pracích by měla být zohledněna změna emisního faktoru během dne a v průběhu roku v různých situacích a mezní emisní faktor by měl být vypočten pro konkrétní podkategorie národního fondu budov, včetně předpovědi budoucích scénářů týkajících se budoucího složení energetického sektoru, flexibility a inteligentního řízení energetické sítě a flexibility a inteligentního řízení budov (jako příklady takovýchto studií mohou sloužit práce Kiss et al. (Kiss, Kácsor and Szalay, 2020) nebo Clauß et al. (Clauß *et al.*, 2019)).

Dalším zdrojem nejistoty je skutečnost, že emisní faktory nebyly použity dynamicky a nebyly zohledněny některé zpětné vazby. Například snížení emisních faktorů pro plyn i dálkové vytápění by se mělo projevit ve snížení emisního faktoru pro kombinovanou výrobu elektřiny a tepla v teplárnách.

Emisní faktory pro obnovitelné zdroje energie byly považovány za nulové, ale ve skutečnosti tomu tak není. Například k získání tepla ze solárních kolektorů je zapotřebí pomocná energie, která byla zanedbána. Podobně byl nulový emisní faktor použit pro biomasu, protože se předpokládalo, že je splněna podmínka obnovitelnosti, což znamená udržitelné pěstování biomasy tak, aby se nespotřebovávalo více biomasy, než je možné vypěstovat. Není však jisté, zda bude tato podmínka v budoucnu splněna. Byly rovněž zanedbány emise související s těžbou a zpracováním biomasy.

Nejistoty v emisních faktorech byly částečně vyřešeny provedenou citlivostní analýzou pro cílový rok 2050, která ukázala, jak se jednotlivé scénáře chovají při uvažování postupného snižování emisních faktorů.

Dalšími zdroji nejistoty jsou předpoklady budoucího vývoje podílu zdrojů energie v budovách, a tedy různých paliv nebo nosičů energie. Definování jejich scénářů předcházela odborná diskuse a analýza dostupných dokumentů. Odhadli jsme, že vliv odchylky od předpokládaného podílu zdrojů v budovách je menší než vliv nepřesnosti emisních faktorů.

Určité nejistoty vyplývají z povahy vstupních údajů o časovém vývoji konečné spotřeby energie v budovách, které vycházely ze zjednodušeného energetického modelu a předpokladů o budoucím vývoji fondu budov.

Kromě toho existují nejistoty v okrajových klimatických podmínkách. V předchozí studii z roku 2016 (Lupíšek, 2019) byla spotřeba energie modelována ve dvou klimatických scénářích, RCP4.5 a RCP8.5, s cílem určit dopad změn klimatických podmínek v České republice na konečnou spotřebu energie v budovách. S ohledem na očekávaný nárůst teplot v obou klimatických scénářích byl do energetického modelu doplněn předpoklad nárůstu spotřeby pro chlazení a klimatizaci a poklesu spotřeby pro vytápění. Výsledným efektem bylo snížení spotřeby energie v jednotlivých scénářích v roce 2050 o 1,7 % až 2,3 % pro RCP4.5 a 5,5 % až 6,4 % pro RCP8.5 ve srovnání se základním scénářem. Toto snížení by mělo vliv i na emise. Vzhledem k relativně malým rozdílům ve spotřebě a relativní pracnosti výsledků modelování v této aktualizované studii nebyly tyto rozdíly zahrnuty.

Energeticky účinná modernizace stavebního fondu bude spojena s produkcí souvisejících emisí skleníkových plynů, které se uvolňují v důsledku těžby surovin, výroby stavebních materiálů a energetických systémů, jejich dopravy a stavebních procesů při jejich zabudování. Tyto svázané emise zatím nebyly důkladně zvažovány, protože nebyly považovány za významné ve vztahu k provozním emisím. Jakmile se však podaří snížit provozní emise z budov na nulu, kombinované emise ze stavebních výrobků a systémů TZB se stanou významnějšími a významně ovlivní celkovou produkci emisí skleníkových plynů souvisejících se stavebním fondem, jak naznačují nedávné studie (Röck *et al.*, 2020). Dobrý příklad různých materiálových úvah v takových analýzách je uveden ve studii kolegů z ETH (Göswein *et al.*, 2021).

5.3.2. Diskuse výsledků v kontextu předchozích studií

Ačkoli předchozí studie z roku 2016 uváděla podíl budov na národní produkci CO_2 ve výši 43 %, tato upřesněná studie uvádí podíl 34,7 %, což se blíží evropskému průměru 36 %, který uvádí Evropská komise (European Commission, 2019).

Vypočtený potenciál snížení produkce CO_2 v NFB v roce 2050 se pohybuje od 27,6 % do 52,0 % bez zohlednění využití BIPV a od 43,6 % do 86,9 % při zohlednění rychlého využití BIPV. Tyto údaje nejsou srovnatelné s relativně nízkým potenciálem snížení emisí uváděným z asijských zemí zmíněných v úvodu, kde se očekává masivní nárůst fondu budov. Výsledná čísla jsou však kompatibilní s rozsahem potenciálu úspor skleníkových plynů pro rok 2050 z Německa (35-65 %) (Bürger, 2013; Bürger *et al.*, 2016, 2019) a s čísly prezentovanými (Kranzl *et al.*, 2019) pro Česko (CZ-ENTRANZE pro rok 2030: 40 %; CZ-Mapping pro rok 2030 37 %; CZ-Briskee pro rok 2030: 38 %; CZ-Progressh pro rok 2030: 26 %). Zpráva neobsahuje české údaje pro rok 2050, ale údaje pro rok 2050 pro sousední Slovensko jsou 72 % (ZEBRA), pro Německo 70 % (ZEBRA) a pro Polsko 60 % (ZEBRA).

6. Budovy zohledňující klimatické cíle

V této kapitole jsou použity vybrané texty ze společného článku *Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions*, který vzniknul v rámci mezinárodní spolupráce v IEA EBC Annex 72 (Habert *et al.*, 2020).

6.1. Problémy alokace klimatických cílů na budovy

Aby bylo možné cokoliv řídit, je potřeba toto umět nejdříve měřit a umět jasně přiřadit role a úkoly jednotlivým aktérům. V kontextu emisí skleníkových plynů není zatím v tomto ohledu zcela jasno. Existuje celá řada možných způsobů alokací uhlíkového rozpočtu na jednotlivé národní státy, ale dosud nedošlo ke všeobecné shodě, jak postupovat. Podobná nebo ještě komplikovanější situace je na úrovni fondů budov nebo dokonce na úrovni jednotlivých budov, a to z několika důvodů. Prvním důvodem je špatná statistická vymezitelnost – pod pojmem „budovy“ rozumíme celou řadu činností, které se v různých statistikách objevují na různých místech – a tedy není přesně identifikováno ani statisticky sledováno, jakou produkci emisí budovy ve skutečnosti představují. Druhým důvodem je, že není dán jasný požadavek nebo princip, podle kterého by se dalo rozhodnout, o kolik se mají emise v budovách snížit, a není rovněž jasně přidělená zodpovědnost, kdo by takové limity měl určovat a garantovat.

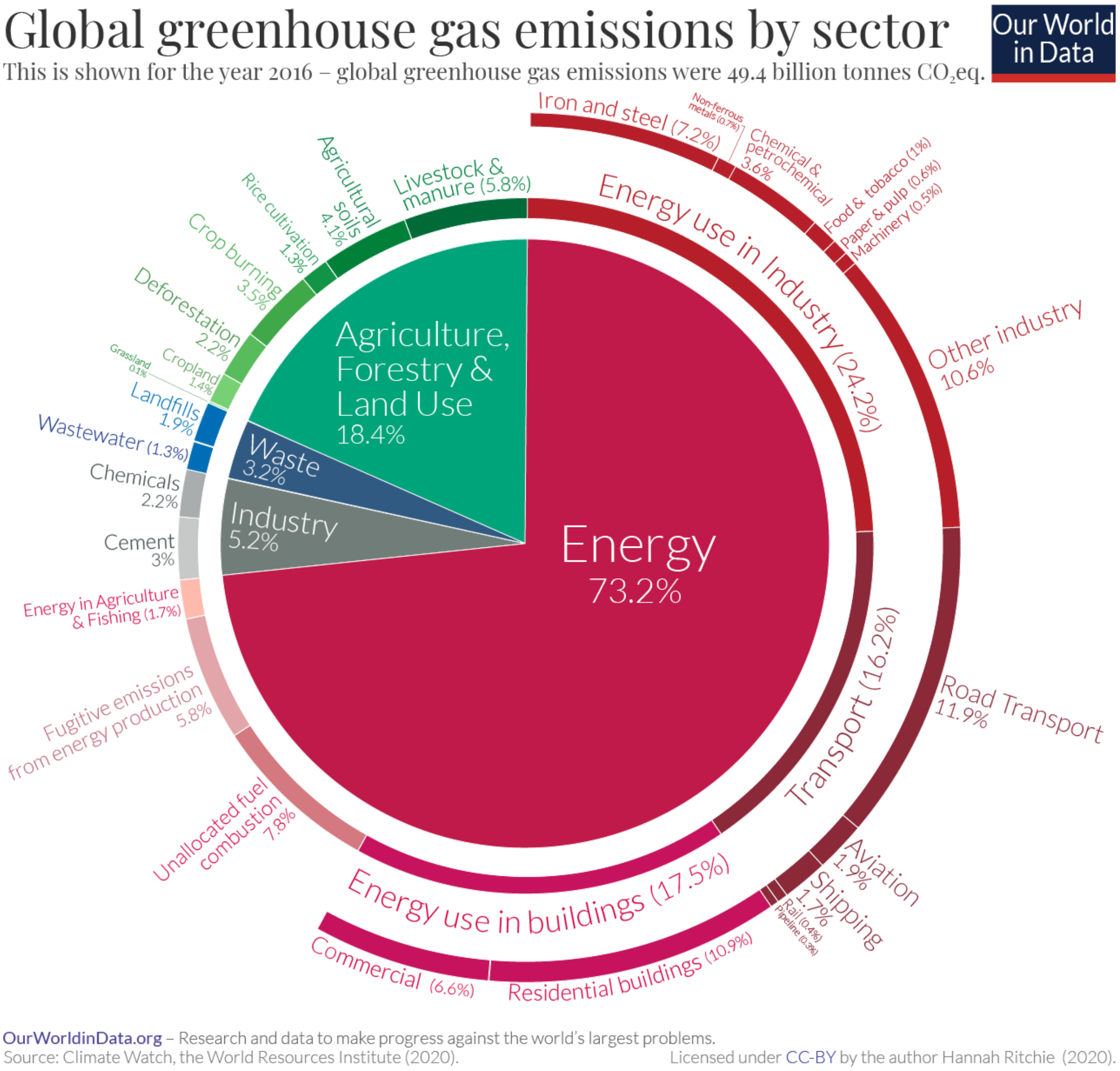
6.2. Problematika statistické klasifikace aktivit životního cyklu budovy

Na aktivity spojené s uhlíkovou stopou budov lze pohlížet z mnoha úhlů a podle různých hledisek. Jedním z možných přístupů ke statistickému přiřazení emisí k budovám je odvětvové dělení. Další možností je hierarchický pohled na základě zodpovědností za provoz budov. Možná je i technická klasifikace aktivit pomocí obecného schématu životního cyklu budovy. A v neposlední řadě lze na budovy pohlížet z hlediska uspokojování různých potřeb společnosti.

Na Obr. 12 je přehled globálních emisí skleníkových plynů členěných podle odvětví průmyslu. Budeme-li se snažit v něm lokalizovat všechny dopady, které nějakým způsobem souvisí s budovami, zaujme na první pohled položka „spotřeba energie v budovách“ (celkem 17,5 %). Ta v sobě ovšem zahrnuje pouze část užívání budov a aktivity v nich, ale nejsou v ní obsaženy dopady na klima související s výstavbou budov, jejich údržbou, ostatními provozními dopady kromě spotřeby energie, renovací, a nakonec demolicí dosloužilých budov. K budovám by tedy dále bylo možné alokovat další podíly emisí:

- Cementářský průmysl (z celkových 3 % bude podíl budov odhadem minimálně třetinový, zbytek bude připadat na infrastrukturu);
- Ocelářský průmysl (celkem 7,2 %, určitý podíl připadne na ocelové konstrukce pro budovy);

- Chemický průmysl (celkem 3,6 %, v budovách se čím dál více využívají plasty, podíl na celkových emisích však bude spíše malý);
- Ostatní průmysl (celkem 10,6 %, určitý podíl bude připadat na stavební výrobky, nebylo podrobně zjišťováno, co všechno tato položka zahrnuje);
- Odlesňování (celkem 2,2 %, dřevo je klíčovým stavebním materiálem v řadě regionů světa);
- Doprava (celkem 16,2 %, určitý podíl na ní bude mít doprava stavebních materiálů);
- Skládkování (určitý podíl z celkem 1,9 %, stavebnictví se podílí na vzniku odpadů zhruba z 1/3, na druhou stranu části budov obvykle nejsou příčinou vzniku skládkových plynů, takže podíl bude jistě menší);
- Nakládání s odpadními vodami (celkem 1,3 %, významná část odpadních vod vzniká v budovách).


Global greenhouse gas emissions by sector

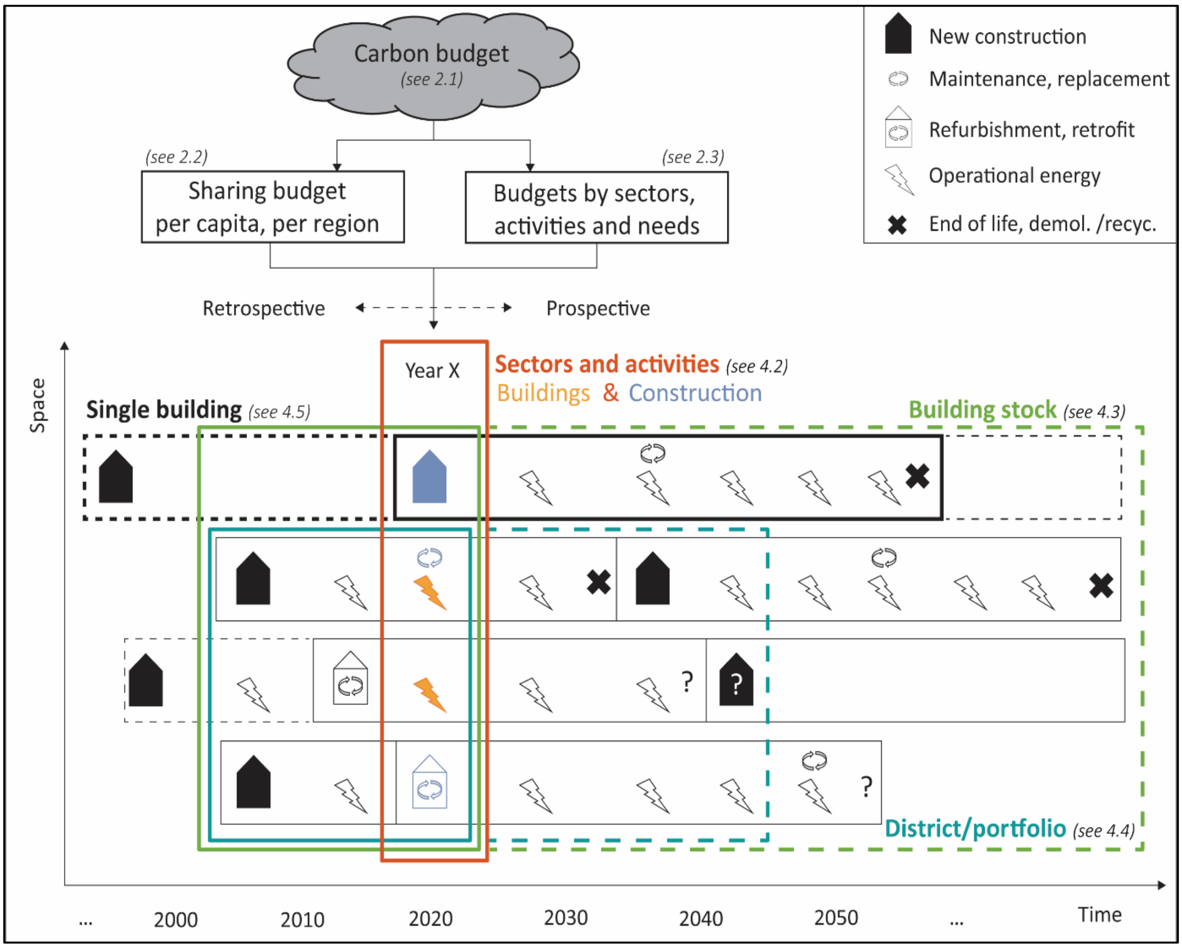
This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO_2eq.

OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Climate Watch, the World Resources Institute (2020).
Licensed under CC-BY by the author Hannah Ritchie (2020).

Obr. 12: Zdroje emisí skleníkových plynů podle odvětví (Ritchie and Roser, 2020).

Dalším přístupem je pohled přes uspokojování lidských potřeb, ke kterému je možné použít dostupné výpočty osobní uhlíkové stopy a v jejím rámci se pokusit analyzovat aktivity související s budovami. Oblast potřeb "bydlení" souvisí s oblastí činnosti "obytné budovy", (Jenny, Grütter and Ott, 2014; Rao and Min, 2018), ale tím je pouze částečně pokryt provoz rezidenčních budov. Sledování ostatních aktivit a dalších typů budov je obtížné.

Hierarchickým přístupem je myšlen tradiční přístup, kde stát (nebo v některých státech region) regulativně určuje požadavky na budovy, za které odpovídá vlastník. Další požadavky na budovy potom může stanovit místní samospráva formou regulačního plánu. Různou úroveň závaznosti mají technické normy. Vnější regulace je doplněna o dobrovolné aktivity, případně závazky vlastníka jedné nebo více budov, který může z různých důvodů usilovat o vyšší než normou či regulací nařízené standardy na své nemovitosti. Pohled vlastníka souboru budov (ať už veřejného nebo soukromého) je zobrazen na Obr. 13.

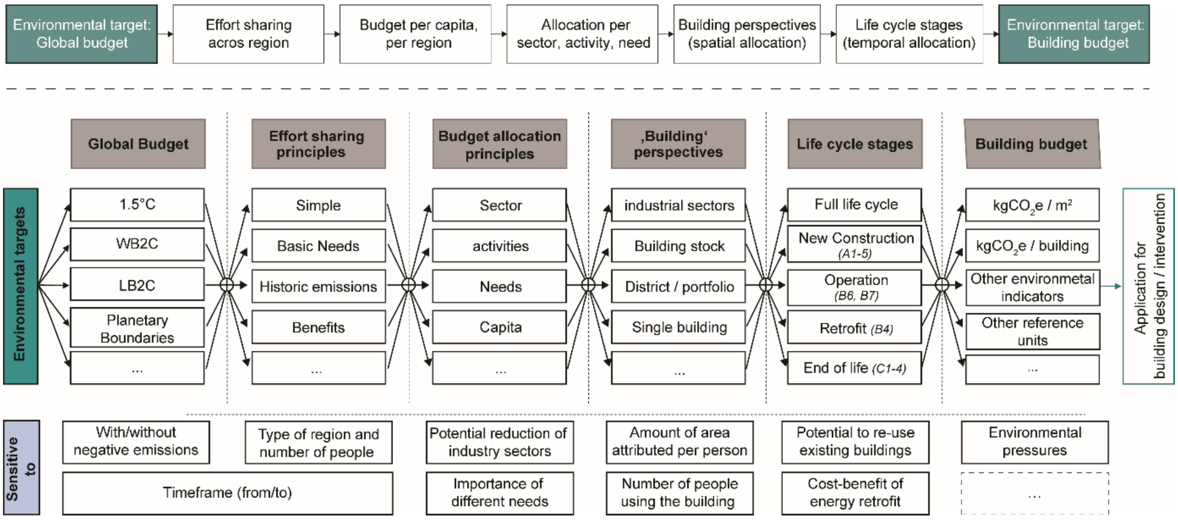


Obr. 13: Problém uhlíkového rozpočtu z hlediska vlastníka souboru budov (Habert et al., 2020).

Vlastník souboru budov má portfolio nemovitostí, které spravuje. Ty se v daném roce (pro který by měly být určeny limity uhlíkové stopy) nachází v různých fázích svého životního cyklu. Některé budovy mohou být ve výstavbě nebo procházet zásadní rekonstrukcí, pak jsou dominantním zdrojem uhlíkové stopy budovy emise spojené se stavebními procesy, kterým předcházela produkce skleníkových plynů spojená s výrobou stavebních materiálů a prvků. Nebo jsou ve standardním provozu, a pak dominují emise z provozu budov. Některé budovy mohou být na konci životnosti a může probíhat jejich odstranění. Všechny tyto situace by bylo potřeba metodicky podchytit, pokud má být možné co nejpřesněji vyčíslit dopady budov na klima a nějakým způsobem je řídit.

6.3. Možné způsoby alokace limitů emisí skleníkových plynů

Jak bylo uvedeno výše, není zatím společenská shoda na tom, které principy a jak používat v alokaci uhlíkového rozpočtu mezi jednotlivé státy a jednotlivé aktéry. Možnosti, které se nabízejí jsou shrnuty na Obr. 14.



Obr. 14: Rozhodovací strom pro definici rozpočtu, který ukazuje různé kroky a rozhodnutí, jež je třeba přijmout a specifikovat pro definici rozpočtů (Habert et al., 2020). Několik aspektů v této definici je citlivých na specifické charakteristiky země (např. počet osob, historické emise atd.) a také citlivých na aspekty chování (např. počet osob využívajících budovu a plochu na osobu).

7. Příklad použití cílů Pařížské dohody pro rok 2030 pro stanovení referenčních hladin pro rezidenční budovy v podmínkách ČR

Tato kapitola je založena na článku *Carbon Benchmark for Czech Residential Buildings Based on Climate Goals Set by the Paris Agreement for 2030* (Pálenský and Lupíšek, 2019), který vycházel z diplomové práce Davida Pálenského (Pálenský, 2019).

Hlavním hlavním cílem práce bylo:

- Navrhnout referenční úroveň z hlediska emisí skleníkových plynů pro nové obytné budovy;
- Provést případovou studii pro porovnání obvyklého návrhu budov s referenční úrovní;
- Navrhnout zlepšení návrhu vedoucí ke splnění stanoveného referenční hladiny;
- Zhodnotit, zda jsou úrovně emisí skleníkových plynů požadované pro splnění cílů stanovených Pařížskou dohodou v českých podmínkách realizovatelné, nebo zda představují příliš radikální zlepšení návrhu budov, a je tedy třeba provést systémovější změny ve způsobu, jakým v současnosti navrhujeme a stavíme obytné budovy.

7.1. Nastavení referenční hladiny

Cílem práce bylo navrhnout referenční úroveň odshora dolů, která by odrážela globální cíle emisí skleníkových plynů stanovené Pařížskou dohodou. Východiskem byla zpráva Emissions Gap Report 2018 (EGR) (UN Environment, 2018), která se zabývala různými scénáři budoucího vývoje globálních emisí skleníkových plynů. Stanovila maximální množství globálních emisí skleníkových plynů, které lze vypustit v roce 2030 tak, aby nárůst průměrné globální povrchové teploty stále zůstal pod cílovou hodnotou 2 °C respektive 1,5 °C ve srovnání s předindustriální érou. V tabulce 3.1 na straně 19 EGR uvádí maximální globální množství emisí skleníkových plynů v roce 2030 ve výši 40 Gt $CO_{2,ekv.}$ pro cíl 2 °C a pouze 24 Gt $CO_{2,ekv.}$, aby nárůst teploty zůstal pod 1,5 °C (v obou případech s 66% pravděpodobností), což představuje snížení emisí skleníkových plynů přibližně o čtvrtinu, resp. o více než polovinu ve srovnání s ročními emisemi skleníkových plynů.

Aby bylo možné stanovit referenční hodnotu, bylo třeba emise pro rok 2030 z globálního údaje přiřadit k jednotlivým budovám v České republice. Jak bylo řečeno výše, diskuse kolem toho, jaké principy přidělování uhlíkového rozpočtu nebo emisních povolenek by měly být použity, aby byla zajištěna spravedlnost, nebo jaké mechanismy sdílení zátěže by měly být použity, stále probíhá. Pro účely této práce bylo použito rovnoměrné rozdělení na obyvatele s využitím prognózy světové populace v roce 2030 (Statista, 2019). Maximální roční emisní alokace 2030, tj. 40 a 24 Gt $CO_{2,ekv.}$, byly vyděleny prognózovaným počtem obyvatel 8,55 miliardy. Výsledkem výpočtu byl roční osobní limit ve výši 4,68 a 2,81 t $CO_{2,ekv.}$ na obyvatele.

Pro určení budoucího podílu bydlení na emisích skleníkových plynů na obyvatele byl použit princip kontrakce, tedy zachování stávajícího poměrného podílu budov pro bydlení při snížení celkového uhlíkového rozpočtu v roce 2030. Pro výpočet emisního podílu fondu budov byla požita hodnota 23,35 %, která představovala odhadovaný podíl bytového fondu na národních emisích CO_2 v roce 2014 (Lupíšek, 2016). Výpočet této hodnoty je uveden v (Lupíšek, 2019), který údaje pro rok 2015 mírně aktualizoval. Vynásobením osobního příspěvku 23,35 % vzniknula hodnota ročního osobního příspěvku pro rok 2030 pro bydlení ve výši 1,09 t $CO_{2,ekv.}$ pro cíl 2 °C a 0,66 t pro cíl 1,5 °C, kterou lze následně extrapolovat na příspěvek pro obytnou budovu vynásobením těchto čísel plánovaným počtem obyvatel budovy (viz Tab. 16).

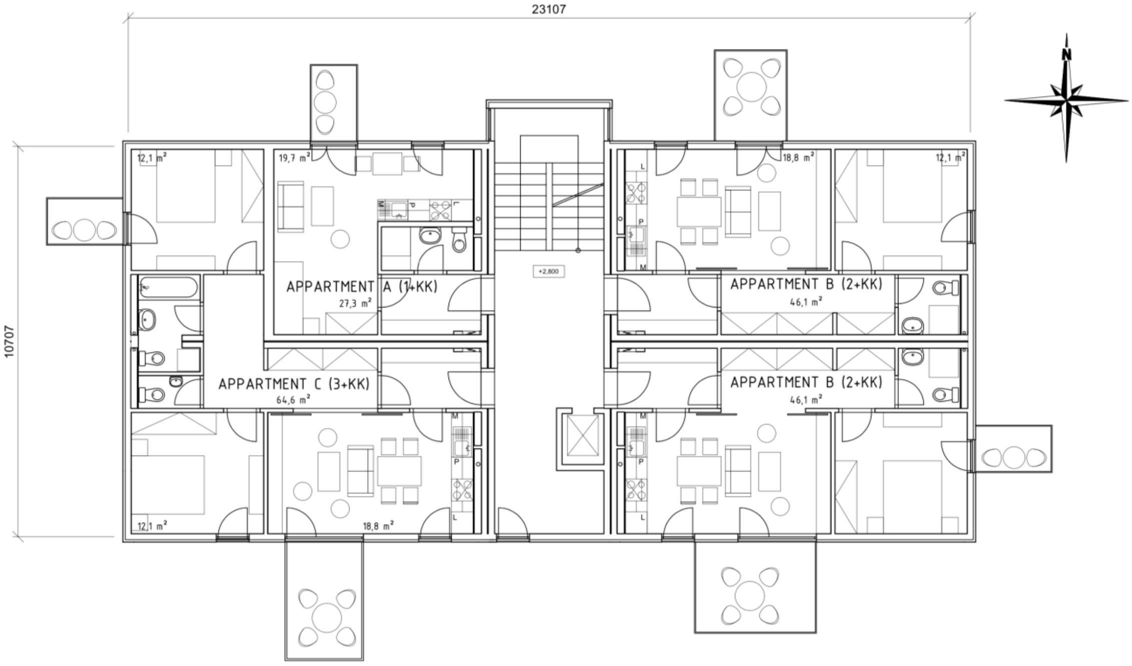
Tab. 16 Stanovení emisních požadavků na budovu pro klimatické cíle 1,5 a 2,0 °C

Klimatický cíl	**1,5 °C**	**2,0 °C**	
Limitní hodnoty emisí dle Emissions Gap Report 2018	24	40	Gt $CO_{2,ekv.}$/rok
Počet obyvatel v 2030	8,55	8,55	mld.
Přepočet na obyvatele	2,81	4,68	t $CO_{2,ekv.}$/os.rok
Podíl bytového fondu	23,35	23,35	%
Přepočet	0,66	1,09	t $CO_{2,ekv.}$/os.rok
Počet nájemníků	26	26	os
Emisní požadavek na bytový dům	**17,04**	**28,40**	**t $CO_{2,ekv.}$/rok**

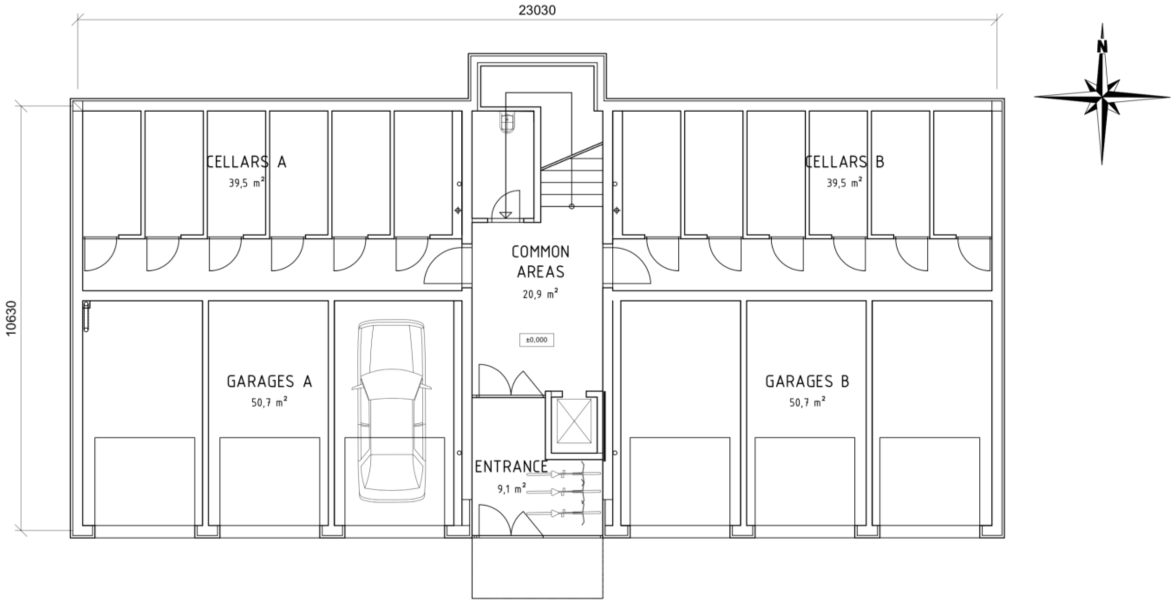
7.2. Popis budovy použité v případové studii

Pro účely této případové studie byla vybrána čtyřpodlažní obytná budova jednoduchého obdélníkového tvaru s plochou střechou (viz Obr. 15, Obr. 16 a Obr. 17). Celková čistá podlahová plocha budovy činila 1 045 m^2 a v nadzemních podlažích se nacházelo 11 bytů pro 26 obyvatel; celkový objem budovy vypočtený z vnějších rozměrů činil 3 572 m^3. V přízemí se nacházela technická místnost, parkovací stání a skladovací prostory pro byty.

Obr. 15: Budova z případové studie. Návrh a vizualizace: Jan Růžička.



Obr. 16: Budova z případové studie – rozložení typického podlaží (rozměry v mm).



Obr. 17: Budova z případové studie – rozložení přízemí (rozměry v mm).

Původní projekt, který představoval běžný standard pro nové bytové domy na českém trhu, měl konstrukční zdivo z keramických dutinových cihelných bloků a podlahové konstrukce z keramických panelů o tloušťce 230 mm. Konstrukce dvojité střechy s provětrávanou dutinou byla z masivních dřevěných prvků. Vnitřní příčky byly z dutinových cihel a omítek. Konstrukce schodišť byly zhotoveny ze železobetonu a konstrukce balkonů z oceli. Vnější stěny byly zatepleny vnějším tepelněizolačním kompozitním systémem o tloušťce 160 mm z pěnového polystyrenu s tenkovrstvou vnější omítkou a střecha byla zateplena 260 mm skelné vaty v dřevěné konstrukci. Průměrná hodnota U byla 0,47 W/m^{2}K.

Otopná soustava se skládala z kondenzačního plynového kotle, který ohříval centrální zásobník o objemu 750 l, a byl spojen s dvoutrubkovým protiproudým rozvodem tepla s deskovými otopnými tělesy. Celková koncepce větrání byla založena na přirozeném větrání a podtlakové větrání bylo instalováno pouze v místnostech s největší produkcí škodlivin, jako je toaleta, koupelna a kuchyně. Přívod vzduchu zajišťovaly větrací štěrbiny v oknech a obvodových stěnách. Chlazení nebylo potřeba.

7.3. Okrajové podmínky a postup výpočtu emisí skleníkových plynů

Pro účely této studie byla použita metoda popsaná v pokynech pro hodnocení národního systému certifikace udržitelnosti SBToolCZ pro obytné budovy (Vonka *et al.*, 2013; Vonka, Hajek and Lupisek, 2013). Indikátor E.02 potenciál globálního oteplování definuje postup výpočtu celkových ročních emisí $CO_{2,ekv.,}$ který vychází ze zjednodušeného posouzení životního cyklu (LCA), jež zahrnuje roční provozní emise i anualizované svázané emise z etap životního cyklu A1-A3 a B4. Konkrétní svázané emise skleníkových plynů byly převzaty z databáze *ecoinvent* (Wernet *et al.*, 2016).

Provozní emise skleníkových plynů byly vypočteny na základě energetického modelování a simulací a emisní faktory byly stanoveny z vypočtené spotřeby energie a energonositelů. Energetické modelování bylo provedeno pomocí softwaru Energie 2017 společnosti SVOBODA SOFTWARE podle národní metodiky vyhlášky Ministerstva průmyslu a obchodu č. 78/2013 Sb., která stanovuje metodu výpočtu měsíční potřeby energie v souladu s národní normou ČSN 730540-2 a mezinárodními normami EN ISO 13790, EN ISO 13789 a EN ISO 13370. Zahrnuje spotřebu energie na vytápění, větrání, klimatizaci, přípravu teplé užitkové vody (TUV), osvětlení a pomocnou energii. Spotřeba domácích spotřebičů nebyla do výpočtu zahrnuta. Výroba energie ze solárních kolektorů byla vypočtena metodou B podle normy EN 15316-4-3.

Potřeba energie na vytápění byla vypočtena na základě průměrných měsíčních teplot. Pro výpočet solárních zisků byly použity hodnoty celkového slunečního záření. Teploty i osvity byly převzaty z národní normy ČSN 73 0331-1 a představovaly průměrné údaje pro ČR.

Vnitřní teplota v obytných prostorách byla stanovena na 21 °C. Schodiště s přilehlými chodbami nebylo považováno za vytápěné, ale protože získávalo teplo z bytů, byla uvažovaná teplota 16 °C. Přízemí s garážemi nebylo vytápěno vůbec a mělo izolovaný strop; teplota pro tuto zónu byla uvažována 5 °C.

Pro větrání byly použity hodnoty 0,3 h-1 (455 m^3/h čerstvého vzduchu pro celou budovu). U mechanického větrání byla vypočtená účinnost zpětného získávání tepla 77 %. Vnitřní tepelné zisky od obyvatel byly uvažovány jako 2,0 W/m^2 (70 % času) a od spotřebičů jako 3,0 W/m^2 (20 % času). Měrná spotřeba energie na osvětlení v základní variantě činila 4,4 kWh/m^2 a ve vylepšených variantách s ohledem na osvětlení světelnými diodami (LED) byla tato hodnota 1,9 kWh/m^2.

Výpočet energie na přípravu teplé vody byl uvažován jako 35,0 l na osobu a den, což činilo 332,2 m^3 teplé vody za rok (ohřáté od 10 do 55 °C). Pomocná energie zahrnovala energii čerpadel a monitorovacích a řídicích systémů topného systému. Plynové kondenzační kotle měly vypočtenou účinnost 95 % a kotle na pelety 86 %.

Emisní faktory pro energetické nosiče byly převzaty z pokynů pro hodnocení SBToolCZ (Vonka *et al.*, 2013): elektřina 207,4 g $CO_{2,ekv.}$/MJ, zemní plyn 87,1 g $CO_{2,ekv.}$/MJ a dřevěné pelety 9,2 g $CO_{2,ekv.}$/MJ (v České republice je biomasa z dřevního odpadu považována za obnovitelný zdroj energie, který splňuje kritéria uhlíkové neutrality podle Mezivládního panelu pro změnu klimatu (IPCC)).

Základem pro hodnocení emisí skleníkových plynů bylo sestavení výkazu výměr hlavních prvků budovy. Hodnoty emisí skleníkových plynů pro použité materiály a stavební výrobky byly získány z katalogu fyzikálních a ekologických profilů stavebních prvků pro novostavby a rekonstrukce envimat.cz (Hodková *et al.*, 2011). V souladu s pokyny pro posuzování byly do výpočtů zahrnuty následující prvky:

- založení,
- hydroizolační vrstvy,
- zhutněný zásyp, zásypový materiál (dovezený z místa mimo stavbu),
- svislé a vodorovné konstrukční prvky, včetně převislých konstrukcí,

- střešní konstrukce,
- střešní palubu,
- schodiště,
- zábradlí,
- vnitřní oddíly,
- nenosné obložení,
- povrchové úpravy,
- finální podlahová krytina,
- okna a dveře,
- tepelná a zvuková izolace.

Na druhé straně nebyly zahrnuty drobné dokončovací prvky (latě, kovové prvky, kliky a další) a systémy obsluhy budov.

Referenční období studie pro zjednodušené LCA bylo 50 let a modelovaná životnost stavebních prvků se řídila doporučeními uvedenými v pokynech pro posuzování pro každou kategorii materiálů nebo výrobků. Na konci výpočtu byly všechny svázané emise sečteny a vyděleny 50 lety, aby se získala anualizovaná svázaná hodnota.

7.4. Výsledky

7.4.1. Emise skleníkových plynů u budovy z případové studie navržené obvyklým způsobem

Vypočtená celková roční spotřeba energie budovy případové studie navržené obvyklým způsobem činila 101,7 MWh. Více než dvě třetiny energie se spotřebovaly na vytápění (69,9 MWh/a), o něco více než čtvrtina na přípravu TUV (28,4 MWh/a), 2,8 MWh/a na osvětlení a 0,6 MWh/a na spotřebu pomocné energie. Většina modelované spotřeby energie byla dodána zemním plynem (98,3 MWh/a) a pouze 3,4 MWh/a bylo dodáno v elektrické energii.

7.4.2. Navrhovaná opatření ke snížení emisí skleníkových plynů původního návrhu

Ke snížení emisí skleníkových plynů a emisí z provozu byla navržena následující opatření:

- O1: Změna teplotního zařazení – nebytové prostory převedené na nevytápěné nebo pouze částečně vytápěné.
- O2a: Snížení tepelných ztrát – tepelná izolace obvodových konstrukcí na základě hodnot U požadovaných pro pasivní domy podle ČSN 730540 (obvodové stěny 0,18 W/m^{2}K, střecha 0,15 W/m^{2}K, okna 0,71 W/m^{2}K, dveře 1,50 W/m^{2}K), optimalizace tepelných vazeb (0,02 W/m^{2}K).

- O2b: Snížení tepelných ztrát – tepelná izolace obvodových konstrukcí na základě hodnot U doporučených pro pasivní domy ČSN 730540 (obvodové stěny 0,12 W/m^{2}K, střecha 0,10 W/m^{2}K, okna 0,55 W/m^{2}K, dveře 1,50 W/m^{2}K), maximální optimalizace tepelných vazeb (0,02 W/m^{2}K).
- O3a: Snížení svázaných emisí – volba ekologicky šetrných výrobků a materiálů (vápenopískové cihly pro stěnové konstrukce a železobetonové předpjaté dutinové panely pro stropní konstrukce).
- O3b: Výběr ekologicky šetrných výrobků a materiálů (dřevěná konstrukce: systém two-by-four).
- O4: Nízkoemisní teplo – volba nízkoemisního zdroje/energonositele (kotel na dřevní biomasu).
- O5: Osvětlení – instalace energeticky úsporných zářivkových a LED svítidel.
- O6: Mechanické větrání s rekuperací tepla (účinnost 77 %) - snížení tepelných ztrát větráním, využití odpadního tepla.
- O7: Vakuové solární kolektory – využití solární energie pro předehřev TUV (80 m$^{2)}$.
- O8a: (30 m$^{2)}$, 5,4 kWp, účinnost systému 15 %, orientace na jih 35°.
- O8b: (50 m$^{2)}$, 9,0 KWp, účinnost systému 15 %, orientace na jih 35°.

7.5. Variantní sady opatření ke zlepšení

Bylo navrženo následujících šest variant sad opatření ke zlepšení (přehled sad je uveden v Tab. 17):

- **S1** (O1, O4, O5): S1 byla kombinací základních opatření s minimálními změnami ve fungování budovy nebo změnami v návrhu (kotel na biomasu, účinné LED osvětlení a snížení vnitřní teploty na hlavních chodbách). Opatření byla zaměřena na snížení množství provozních emisí skleníkových plynů.
- **S2** (O1, O3a, O4, O5, O7): S2 doplňuje předchozí variantu S1 s důrazem na snížení podílu emisí skleníkových plynů pomocí stavebního systému v podobě vápenopískových cihel pro stěnové konstrukce a železobetonových předpjatých dutinových panelů pro stropní konstrukce. Varianta byla rovněž doplněna o systém vakuových solárních kolektorů sloužících k přípravě teplé vody (80 m^{2,} orientace na jih 35°, v kombinaci s akumulační nádrží 4 500 l).
- **S3** (O1, O2a, O3b, O4, O5, O6, O7): S3 kombinuje navržená opatření s důrazem na nízkoenergetickou náročnost budovy. Všechny konstrukce splňovaly požadované hodnoty součinitele prostupu tepla pro pasivní budovy; tepelné spoje a mosty byly optimalizovány na minimální hodnoty. Technické systémy byly doplněny systémem nuceného rovnovážného větrání s rekuperací tepla. Konstrukční systém byl nově navržen jako dřevostavba v systému two-by-four v podobě montovaného

dřevěného rámu vyplněného tepelnou izolací. Stropní konstrukci tvořil dřevěný trámový strop.

- **S4** (O1, O2a, O3b, O4, O5, O6, O7, O8a): S4 byl založen na kombinaci opatření uvedených v S3. Kromě toho byl použit systém fotovoltaických panelů pro snížení spotřeby elektrické energie, která by se zvýšila díky systémům nuceného větrání a čerpadlům se solárními kolektory.
- **S5** (O1, O2a, O3b, O4, O6, O7, O8a): S5 byla založena na kombinaci opatření uvedených v S4 s tím rozdílem, že zdrojem tepla byl původní plynový kondenzační kotel.
- **S6** (O1, O2b, O3b, O5, O6, O7, O8b): S6 byl postaven na základě S5 tak, aby splňoval emisní požadavky při zachování původního zdroje tepla v podobě plynového kondenzačního kotle (S5 emisní požadavky nesplňoval). Kombinace opatření vycházela ze S5 s několika zásadními rozdíly. Obvodové konstrukce byly navrženy na nejnižší hodnoty doporučených hodnot $U_{pas,20}$ pro pasivní budovy podle ČSN 73 0540-2. Tepelné spoje byly co nejvíce redukovány. Fotovoltaické (FV) moduly byly použity k pokrytí spotřeby elektrické energie pro provoz nuceného větrání, pomocné energie, osvětlení a části výroby teplé vody. Přebytky byly dodávány do energetické sítě (ačkoli jsme tyto přebytky nezohledňovali v provozní emisní bilanci). Oproti předchozím variantám se celková plocha panelů zvětšila na 50 m^2.

Tab. 17 Přehled šesti souborů opatření na úsporu emisí skleníkových plynů (GHG).

Varianty	**Původní stav**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Opatření na úsporu emisí skleníkových plynů							
O1 Změna teplotní zóny		✓	✓	✓	✓	✓	✓
O2a Hodnoty U požadované pro pasivní bydlení				✓	✓	✓	
O2b Hodnoty U doporučené pro pasivní bydlení							✓
O3a Vápenopískové cihly, před-pjaté betonové podlahové konstrukce			✓				
M3b Dřevěná konstrukce				✓	✓	✓	✓
M4 Kotel na biomasu		✓	✓	✓	✓		
Osvětlení M5 LED		✓	✓	✓	✓	✓	✓
M6 Mechanické větrání s rekuperací tepla				✓	✓	✓	✓
M7 Vakuové solární kolektory 80 m^2			✓	✓	✓	✓	✓
M8a Fotovoltaické panely 5,4 kWp, 30 m^2					✓	✓	
M8a Fotovoltaické panely 9,0 kWp, 80 m^2							✓
Hodnoty U obálky budovy (W/m2K)							
Vnější stěna (vytápěná plocha)	0.27	0.27	0.27	0.18	0.18	0.18	0.12
Vnější stěna (nevytápěný prostor)	0.62	0.62	0.62	0.38	0.38	0.38	0.38
Vnější stěna – sokl (nevytápěný prostor)	0.57	0.57	0.57	0.38	0.38	0.38	0.38
Patro nad nevytápěným přízemím	0.57	0.57	0.57	0.38	0.38	0.38	0.16
Podlaha na zemi	0.56	0.56	0.56	0.45	0.45	0.45	0.45
Střecha	0.21	0.21	0.21	0.15	0.15	0.15	0.10
Windows	1.50	1.50	1.50	0.71	0.71	0.71	0.55
Vstupní dveře	3.50	3.50	3.50	1.50	1.50	1.50	1.50
Horní vrata (garáže)	3.50	3.50	3.50	1.50	1.50	1.50	1.50
Tepelné spojky	0.05	0.05	0.05	0.02	0.02	0.02	0.00

7.6. Emise skleníkových plynů navrhovaných variant

Rozpis svázaných emisí a modelované spotřeby energie a emisí skleníkových plynů navrhovaných souborů je shrnut v Tab. 18.

Tab. 18 Modelované svázané emise skleníkových plynů, spotřeba energie a emise skleníkových plynů původní budovy (běžný stav) a navrhovaných souborů zlepšení S1-S6.

	Původní stav	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Svázané emise skleníkových plynů (t $CO_{2,ekv.}$)							
Základy	58.1	58.1	58.1	64.6	64.6	64.6	64.6
Vnější stěny	64.9	64.9	63.0	33.3	33.3	33.3	37.1
Vnitřní stěny	52.0	52.0	41.6	13.5	13.5	13.5	13.5
Horizontální struktury	216.2	216.2	156.2	99.0	99.0	99.0	103.1
Ostatní součásti	32.4	32.4	32.4	69.1	69.1	69.1	69.1
Celkem	423.5	423.5	351.2	279.5	279.5	279.5	287.4
Roční spotřeba energie (MWh/rok)							
Vytápění	69.9	80.7	80.7	38.6	38.6	34.1	16.6
Teplá voda pro domácnost	28.4	31.3	29.3	29.3	29.3	27.7	27.7
Vakuové solární kolektory	0.0	0.0	−12.3	−12.3	−12.3	−12.5	−12.3
Mechanická ventilace	0.0	0.0	0.0	1.5	1.5	1.5	1.5
Osvětlení	2.8	1.8	1.8	1.8	1.8	1.8	1.8
Fotovoltaické panely	0.0	0.0	0.0	0.0	−3.2	−3.2	−7.4
Pomocná energie	0.6	0.4	0.8	0.8	0.8	0.8	0.7
Celkem	101.7	114.2	100.3	59.7	56.5	50.2	28.6
Provozní emise skleníkových plynů (t $CO_{2,ekv./rok}$)	33.36	5.35	5.57	5.30	3.25	16.87	10.45
Roční svázané emise skleníkových plynů (t $CO_{2,ekv./a}$)	8.47	8.47	7.02	5.59	5.59	5.59	5.75
Celkové roční emise skleníkových plynů (t $CO_{2,ekv./a}$)	41.8	13.8	12.6	10.9	8.8	22.5	16.2
Dodržení cíle 28,3 t $CO_{2,ekv./a}$ (cíl 2,0 °C)	X	✓	✓	✓	✓	✓	✓
Dodržení cíle 17,2 t $CO_{2,ekv./a}$ (cíl 1,5 °C)	X	✓	✓	✓	✓	X	✓

Sada S1 zahrnovala výměnu kondenzačního plynového kotle za kotel na biomasu, instalaci účinného LED osvětlení a snížení vnitřní teploty na hlavních chodbách. Tato opatření přispěla k výraznému poklesu provozních emisí skleníkových plynů díky úsporám ve spotřebě elektřiny a nízkoemisnímu faktoru biomasy, tj. 9,2 g $CO_{2,ekv.}$/MJ (ve srovnání s emisním faktorem elektřiny 207,4 $CO_{2,ekv.}$/MJ). Na druhou stranu se zvýšila celková spotřeba energie v důsledku snížené energetické účinnosti kotle (kotel na pelety 86 %, původní plynový kotel 95 %), účinnosti rozvodu tepla (kotel na pelety 85 %, původní plynový kotel 98 %) a snížených vnitřních tepelných zisků z osvětlení.

Soubor S2 navázal na soubor S1 a snížil emise skleníkových plynů tím, že nahradil konstrukční materiál stěn ze standardních cihelných bloků vápenopískovými cihlami a předpjatými dutinovými betonovými panely. Dosažené snížení činilo 72,3 t $CO_{2,ekv.}$. U této sestavy se rovněž využilo doplnění vakuových solárních kolektorů, které dodaly 12,3 MWh čisté energie.

Sada S3 kombinovala opatření použitá v sadě S2 s výrazným zlepšením hodnot U obálky budovy, doplněním mechanického větrání s rekuperací tepla a použitím dřevěné konstrukce na stavbu. Zlepšení hodnot U vedlo k výraznému snížení spotřeby tepla, zatímco zavedení mechanického větrání způsobilo výrazné zvýšení spotřeby elektrické energie, což mělo za následek vysoké provozní emise skleníkových plynů v důsledku vysokého emisního faktoru. Přeměna konstrukce na dřevěnou konstrukci snížila celkové emise svázaných skleníkových plynů o dalších 71,7 t $CO_{2,ekv.}$.

Sada S4 byla podobná sadě S3, ale také využívala fotovoltaický systém (5,3 kWp), který dodal dalších 3,2 MWh čisté elektřiny. Umožnila tak snížit provozní emise skleníkových plynů o 2,05 t $CO_{2,ekv.}$.

Sada S5 byla reakcí na situaci, kdy nebylo možné použít kotel na biomasu z důvodu místní regulace emisí zvláštních látek. Měla všechny vlastnosti sestavy S4, ale místo kotle na pelety používala plynový kondenzační kotel. V této variantě budova splňovala emisní cíl 2 °C, ale nesplňovala emisní cíl 1,5 °C.

Sada S6 zahrnovala opatření, která byla nutná k dosažení emisního cíle 1,5 °C, tj. další zlepšení hodnot U obálky budovy a další rozšíření fotovoltaického systému, čímž bylo dosaženo limitů plochy střechy. V důsledku toho se provozní emise snížily na 10,45 t $CO_{2,ekv.}$, což umožnilo dosažení cíle.

7.7. Diskuse

7.7.1. Referenční hodnoty skleníkových plynů pro budovy

V ideálním světě by referenční hodnoty skleníkových plynů nebyly potřeba, protože všechny environmentální externality lidské činnosti by byly zahrnuty v ceně každého výrobku, takže spotřebitelé a investoři by dostávali cenové signály, které by vyjadřovaly chování příznivé pro společnost i životní prostředí, na kterém její fungování závisí. Dalším řešením by byla globální uhlíková daň nebo globální systém obchodování s emisemi, který by zahrnoval lidské činnosti a upravil tak ekonomický systém tak, aby bylo ziskové pouze udržitelné chování. V současné době se to však ani jedno z toho ve světě neděje. Proto potřebujeme nějakou regulaci pro stavebnictví a tato regulace by mohla být založena na referenčních hodnotách skleníkových plynů.

Předložená referenční hodnota emisí skleníkových plynů pro obytné budovy trpí různými zjednodušeními, nedokonalostmi a nejistotami. Hlavní zjednodušení spočívá v tom, že jsme použili rovnoměrné rozdělení zbývajícího uhlíkového rozpočtu (a tedy povolenky na roční emise skleníkových plynů). Jak bylo uvedeno v úvodu, diskuse o tom, jaký druh alokace by měl být použit, stále probíhá a preferovaný princip alokace může být v budoucnu revidován oběma směry. Uhlíkový rozpočet přidělený lidem žijícím v Česku by mohl být vyšší, protože naše současná hodnota na obyvatele je vysoká a její masivní snížení během několika málo let by způsobilo šok. Mohl by však být také nižší, protože Česko (a bývalé Čechy v rámci Rakouského císařství a Československa) je od počátku 20. století vysoce industrializovanou zemí, takže historicky přispívá ke změně klimatu relativně více než rozvojové země, které by měly mít právo na rozvoj. Výsledek této debaty se teprve ukáže, a proto jsme se rozhodli pro rovnoměrný příděl na obyvatele.

Dalším zdrojem nejistoty je samotný zbývající uhlíkový rozpočet, který se v průběhu času mění a tempo jeho vyčerpávání je proměnlivé. Znalosti o změně klimatu se také v čase vyvíjejí a bylo by nutné je průběžně upravovat.

Existuje také nejistota týkající se podílu českého bytového fondu na celkových národních emisích, protože základní studie vycházela z odhadu založeného na modelu českého bytového fondu, který trpí nejistotami. Kromě toho jsou celkové národní emise statistické údaje, které trpí určitou mírou nejistoty.

I s ohledem na tyto nejistoty se však domníváme, že toto cvičení mělo smysl, protože poukázalo na obrovskou propast mezi běžnou stavební praxí a praxí, kterou je třeba přijmout pro dosažení klimatických cílů.

7.7.2. Nejistoty v případové studii

Případová studie trpěla standardními nejistotami zjednodušené LCA: nejistotami v základních údajích o materiálech, emisních faktorech, modelovaných scénářích, přístupu k anualizaci svázaných emisí na základě referenčního období studie a také nejistotami souvisejícími s modelováním energie pomocí měsíční metody.

Výpočet energetické bilance fotovoltaického systému a jeho využitelnosti byl zjednodušen. Pro přesnější výpočty by bylo nutné použít specializovaný software s ohledem na přebytky elektřiny vyrobené z fotovoltaiky, které byly dodávány zpět do energetické sítě. Při podrobnější simulaci vyvstává otázka, zda se má zohlednit emisní bilance a jaký emisní faktor se má použít (skutečný energetický mix, a tedy i emisní faktor se v čase mění).

Do energetického hodnocení budovy nebyla zahrnuta spotřeba elektrické energie pro standardní a nestandardní spotřebiče. Vzhledem k vysokému emisnímu faktoru elektřiny v České republice může mít tato spotřeba významný vliv na hodnotu celkových provozních emisí.

7.7.3. Použitelnost strategií snižování emisí skleníkových plynů z případové studie

Použité strategie snižování emisí skleníkových plynů se řídily dvěma zásadami: zajištění energie ze zdrojů s nízkým emisním faktorem a snížení spotřeby energie. Proto jsme se nejprve snažili provést minimální změny v původním projektu, jednoduše jsme vyměnili plynový kotel za kotel na pelety. Z hlediska emisí skleníkových plynů by to velmi pomohlo (za předpokladu, že je k dispozici udržitelný zdroj dřeva). Kotel na pelety má však sníženou účinnost, což by vedlo ke zvýšení spotřeby energie. Zároveň je v mnoha českých obcích problém se znečištěním ovzduší. Proto by instalace kotlů na pelety, které jsou určitým zdrojem znečištění, ani nebyla povolena. Proto jsme nastavili jiné soubory opatření, které by byly široce použitelné, ale představovaly by výraznější změny v konstrukci budovy. I tyto varianty by mohly trpět dalším druhem omezení. V některých lokalitách by nebylo povoleno připojit k síti velké fotovoltaické systémy s omezenou kapacitou sítě, a proto by byl nutný nějaký druh akumulace elektřiny na místě.

Kromě toho nebyly ve studii při navrhování variantních souborů opatření plně zohledněny některé vlastnosti původní budovy – například nebyla vypočtena požární odolnost nebo akustické parametry navrhovaných řešení nebo nebyly porovnány s budovou v původním stavu.

8. Závěr

8.1. Potenciál národního fondu budov přispět k národním cílům ochrany klimatu

V představené studii byl kvantifikován potenciál snížení emisí CO_2 z provozu českého fondu budov podle aktualizovaných scénářů modernizace budov a byl vyhodnocen možný příspěvek energeticky úsporných opatření aplikovaných na fond budov k národním emisním závazkům.

Výpočty byly založeny na modelované konečné roční spotřebě energie NFB ve čtyřech scénářích modernizace v letech 2016-2050. Výsledky ukázaly, že fond budov vyprodukoval v roce 2016 celkem 36,9 Mt CO_2, přičemž 23,2 Mt CO_2 pocházelo z bytových budov a 13,7 Mt CO_2 z nebytových budov. Podíl obytných budov na národních emisích činil přibližně 21,8 %, podíl nebytových budov 12,8 % a celkový podíl 34,6 %.

Výsledky výpočtu ukázaly potenciál snížení provozních emisí bez zohlednění fotovoltaiky budov CO_2 českého stavebního fondu do roku 2050 v rozmezí přibližně 27,6 % v základním scénáři až 52,0 % v hypotetickém scénáři. Při zahrnutí BIPV se toto snížení pohybuje od 43,6 % do 86,9 %. V porovnání s emisemi z roku 1990 se rozsah snížení za různých předpokladů modernizace budov a rozvoje fotovoltaiky pohybuje mezi 69 % a 93 %.

Za předpokladu vyváženého podílu průmyslových odvětví na snižování emisí skleníkových plynů byl národní klimatický závazek pro fond budov v roce 2050 vypočten na 11,4 Mt CO_2. Výsledné hodnoty pro jednotlivé scénáře byly porovnány s touto cílovou hodnotou. Porovnání hodnot emisí v jednotlivých scénářích uvedených v tabulkách 8 a 9 s maximální cílovou hodnotou potřebnou ke splnění národního emisního závazku ve výši 11,4 Mt CO_2 ukázalo, že závazek lze splnit pouze realizací alespoň progresivního scénáře modernizace budov při současném rozvoji fotovoltaiky. V Hypotetickém scénáři by byl cíl splněn již v roce 2040 a v roce 2050 by se emise z fondu budov blížily cíli jejich úplné dekarbonizace. Základní scénář vedl k téměř dvojnásobným hodnotám ve srovnání s požadovaným cílem pro rok 2050. Vládní scénář překročil cílovou hodnotu o 56 %.

Dosažení skutečně nulových emisí v budoucnu musí být výrazně podpořeno snížením emisních faktorů elektřiny, dálkového vytápění a plynu a/nebo výraznou změnou podílu budov na zdrojích energie tak, aby nebyly využívány zdroje s vysokými emisemi, a/nebo spojením budov s technologiemi zachycování a ukládání uhlíku v budoucnu.

Pro splnění emisního závazku České republiky je nutné do roku 2050 snížit roční národní produkci emisí o 73,8 Mt cO_2. v případě realizace hypotetického scénáře s fotovoltaikou by ČSÚ ušetřil 31,9 Mt CO_2 ročně, což by přispělo ke snížení na národní úrovni snížením emisí celkem o 43,2 % oproti referenční hodnotě emisí z roku 2016.

8.2. Možnosti využití klimatických cílů Pařížské dohody pro rok 2030 pro stanovení referenčních hladin pro rezidenční budovy v podmínkách ČR

V kapitole 7 byl představen možný přístup k aplikaci referenčních hodnot emisí skleníkových plynů pro obytné budovy v České republice stanovených na základě Emissions gap reportu, rovnoměrného rozdělení limitů emisí skleníkových plynů pro rok 2030 mezi prognózovanou populaci a podílu obytných budov na národních emisích.

Pro porovnání emisí skleníkových plynů z běžného návrhu budovy s referenční hodnotou byla použita skutečná konstrukce bytového domu, a to pomocí zjednodušené metody LCA v souladu s národní metodou SBToolCZ. Výsledky ukázaly, že posuzovaný obytný dům navržený standardním způsobem překračuje emisní limit 2,5krát. Na základě posouzení bylo navrženo šest souborů úsporných opatření ke snížení provozních a svázaných emisí skleníkových plynů. Úsporná opatření zahrnovala změnu teplotního zónování, zlepšení hodnot U obálky budovy, výměnu stavebních materiálů za účelem snížení svázaných emisí skleníkových plynů, výměnu zdroje tepla za kotel na biomasu, zavedení LED osvětlení, použití mechanického větrání s rekuperací tepla, doplnění vakuových solárních kolektorů a doplnění fotovoltaických panelů. Nakonec byly varianty porovnány a byla prověřena jejich vhodnost v českých podmínkách.

Předložené zásady jsou použitelné i pro situace v jiných zemích, i když zde stále existuje mnoho zdrojů nejistoty.

8.3. Témata pro další výzkum

Aktuální práce na tématu jak na našem pracovišti, tak v mezinárodní komunita přináší řadu dalších výzkumných témat:

- Ke scénářům rekonstrukcí českého fondu budov by bylo vhodné doplnit studii, která by odhadnula a kriticky zhodnotila **množství svázaných emisí skleníkových plynů spojených s energetickou sanací budov** v jednotlivých scénářích;
- Vytvoření série **případových studií**, pomocí kterých by bylo možné podrobněji stanovit **referenční hladiny** pro různé typologie budov;
- Vytvoření **národního systému zveřejňování a pravidelné aktualizace výše emisních faktorů elektřiny v rozvodné síti** (včetně příslušné metodiky) a vytvoření jednotného **rámce pro výpočet budoucích emisí skleníkových plynů spojených s výrobou elektřiny**. Konkrétně by bylo zapotřebí mít stanovené emisní faktory, které mají být uvažovány ve výpočtech v budoucích letech do roku 2050. Samozřejmě s vědomím, že se jedná o predikce, a s metodikou jejich pravidelných revizí.
- Vytvoření **vhodných pomůcek pro architekty a projektanty**, které by jim usnadnily sledování produkce emisí skleníkových plynů životního cyklu jimi navrhovaných budov již v úvodní od úvodní fáze návrhu;

- **Doplnění chybějící datové základny svázaných emisí skleníkových plynů** pro systémy TZB, pro nové materiály, a pro recyklační procesy;
- Vývoj nových **nových technologií**, které by umožnily budoucí nízkoemisní produkci stavebních výrobků.

V neposlední řadě je potřeba mít na vědomí, že problematika snižování emisí skleníkových plynů jde napříč všemi sektory ekonomiky. Je potřeba o problému uvažovat v souvislostech, nepodlehnout bezhlavé honbě za snížením jednoho konkrétního indikátoru, naopak je zapotřebí spolupracovat s ostatními vědními obory tak, aby se podařilo vybalancovat snahu o ochranu životního prostředí s kulturními a ekonomickými potřebami rozvoje společnosti.

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New trends in sustainability assessment systems – based on top-down approach and stakeholders needs

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Worldwide interest in future-proof buildings is growing, leading to increased demand for suitable methods and systems for assessing and communicating the sustainability of buildings. The number of stakeholders interested in sustainability assessment results as a basis for decision-making is growing.

Ultimately, in order to bring about greater sustainability, stakeholders need to understand their potential impacts, but can only do so if this potential is clearly communicated to them through the system structure and through a language and in a format that suits their needs.

Numerous systems exist, though these do not always meet the above requirements, do not always address all aspects of sustainability, may have certain methodological issues and may cause confusion through their sheer number.

Therefore, there is a clear need for assessment systems to be developed further. This paper proposes that the issues raised can be tackled by a two-pronged approach: Firstly, by adhering to a top-down approach the structure of assessment systems is improved. Secondly, greater attention to stakeholder requirements is to be given.

This paper is based on findings from survey results and on work in progress on the current EU-funded research project SuPerBuildings. It aims to stimulate further development of existing assessment systems in a way that maintains the autonomy of such systems, while bringing them closer together in terms of their content.

Keywords: sustainable building; sustainability assessment; top-down approach; indicators; stakeholders; stakeholder needs

1. Introduction

An intensive debate of sustainability issues in the construction sector led worldwide to the development and implementation of various methods and systems for defining, assessing and communicating the sustainability of buildings. However the debate is ongoing. Further developments are required in order to adapt to new challenges and opportunities in the field.

A first generation of building related sustainability assessment methods and systems concentrated on topics such as energy efficiency, and environmental and indoor environment related issues (e.g. health and comfort). They were designed to support the planning, construction and marketing of green buildings. The indicator systems used emerged from the tradition of energy efficient, resource efficient, environmentally friendly and health conscious construction and as such followed a bottom-up approach.

In the meantime a large number of such systems have emerged, that have successfully contributed to awareness amongst stakeholders, improvements in the planning process and increased demand for green buildings. But the existing methods and systems are difficult to compare. Some are being used globally; others concentrate on local, regional or national specifics. Inevitably this makes for a difficult situation for market players – for example for real estate businesses with an international portfolio. There is therefore a desire to unify methods. This is also the aim of standardisation, of the scientific community and in parts also of the systems providers themselves. However, so far there is no indication that any particular approach will prevail.

In literature much has been written about sustainability assessment methods [1–6], comparisons of systems [7–14] and general issues of assessing the sustainability of buildings [15,16].

Nevertheless there are currently reasons and demands to discuss the direction and content of further developments in this area.

The subject matter of sustainability extends far beyond mere environmental and health aspects and requires the treatment of interrelationships between environmental, social and economic issues. This requires a substantially more complex approach, which needs to be structured clearly. Furthermore, in addition to the common categories such as land use, resources, energy (which can be classified as inputs) and resulting impacts (e.g. on health, on local and global environment, and on financial matters), certain further categories will need to be included into

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sustainability assessments. These need to capture benefits resulting from the use of the building. Sustainability requires a long-term perspective. Consequently, topics such as durability, resistance and adaptability come to the forefront. It is becoming obvious that issues of specifying and assessing also the technical and functional qualities of a building will need to be included in sustainability assessments. It is the technical performance in particular that determines the durability and longevity of the building. Furthermore, whether a building can be adapted to changing user requirements or deconstructed and recycled easily is also down to technical issues, in so far as the technical performance is decisive in ensuring future usability and economic success of the property.

Altogether, this results in further requirements to be covered by assessment methods and the necessity to amend and complement the indicators currently used. Not all existing assessment methods and systems meet these requirements.

Consequently, the first key question arises: how does an assessment system need to be structured and what does it need to contain in order to deal with the full complexity of sustainability assessments?

Increasingly it is also being discussed whether and how far the results of sustainability assessments can be used by third parties such as valuation surveyors and other groups of stakeholders [5,6,17–20].

In addition to their roles in supporting the planning process and marketing, it emerges that assessment systems are establishing themselves as information sources and decision making aids. These new roles also result in further demands on new and existing assessment systems and their development.

Hence a second key question arises: in order to meet the requirements of different stakeholders, how do assessment systems need to be developed and used and how do results need to be presented, so that ultimately the right decisions in the interest of sustainability are being made?

In the light of the two key questions developed above, there is a clear need for many existing systems to be overhauled and developed further. Such development work is an opportunity for systems to also move closer together in terms of content, while retaining the autonomy of their approaches in principle. Consequently there is a need for plausible and practicable recommendations for the further development of existing systems, rather than suggestions for yet another new system.

Therefore this paper will discuss current trends in the thinking regarding the further development of assessment systems and presents an endeavour towards a new generation of assessment systems that follow a top-down approach and encompass sustainability in its fullest extent. Furthermore it makes recommendations for stakeholder-friendly ways of presenting assessment results, which is based on a survey amongst different stakeholders.

The contents that deal with the issues introduced above and presented here constitute selected interim results from the EU-project SuPerBuildings, developed under the leadership of the Centre Scientifique et Technique du Bâtiment (CSTB) in work package 4, and under the over-all project coordination of the Technical Research Centre of Finland (VTT). The thinking behind the top-down approach has been predominantly developed by the Karlsruhe Institute for Technology (KIT), while the survey amongst target and user groups was conducted by the Czech Technical University in Prague (CVUT).

2. Basics and emerging trends

2.1 Standardisation

Technical Committee ISO TC 59 SC 17 'Sustainability in buildings and civil engineering works' is tasked with basic principles of sustainability in the construction sector. A first set of standards regarding such general principles [21], as well as for the development and application of indicators [22] and for the assessment of environmental performance of buildings [23]has already been published.

Technical Committee CEN/TC 350 'Sustainability of Construction Works' is preparing standards for the sustainability assessment of buildings. Based on these developments in international standardisation, Europe-specific rules and regulations are being developed and elaborated. The starting point for this work is that the integrated performance of buildings incorporates environmental, social and economic performance as well as the technical and functional quality, and that these are intrinsically related to each other. The intended result of the work is development of general frameworks for the environmental, social and economic performance, and the development of corresponding assessment methods for buildings. The thinking is strongly rooted in the principles of Life Cycle Assessments (LCA) with some of the authors having been involved in the development and application of LCA tools and methodologies. In the endeavour to bring this thinking to sustainability assessments a life cycle approach and the use of functionally equivalent systems is emphasised as the basis of assessment and quantifiable indicators. Wherever in the life cycle of the construction project the assessment takes place, the contribution of the assessed construction works to sustainable construction will be quantified. The main justifications of the work include that it takes into account the needs of the relevant EU policies related to construction products such as Construction Products Regulation [24], Ecodesign Directive [25] and helps to prevent potential technical trade barriers on internal and international markets. Some standards have already been published [26–29]. Figure 1 shows the main principle of

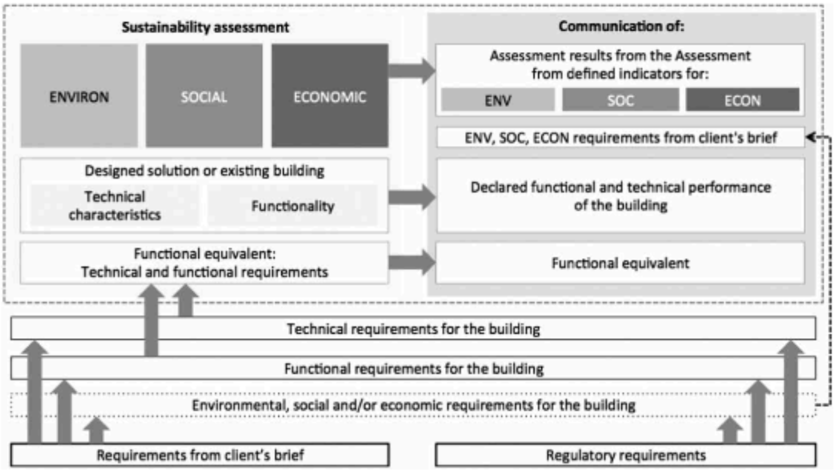

Figure 1. Principle of approaching sustainability assessments of buildings in accordance with standard EN 15643-1 [26].

approaching sustainability according to the current status of CEN-standardisation.

In summary, it can be concluded that international standardisation:

- Assumes that all dimensions of sustainability are to be considered when assessing the sustainability of buildings, meaning that systems have to be specifically extended to include the economic dimension;
- Makes connections between sustainability assessments and the capturing of technical and functional qualities of the buildings;
- Recommends to deduce assessment criteria from the relevant areas of protection;
- Aims to move towards greater use of quantitative methods (LCA – life cycle assessment and LCC – life cycle costing);

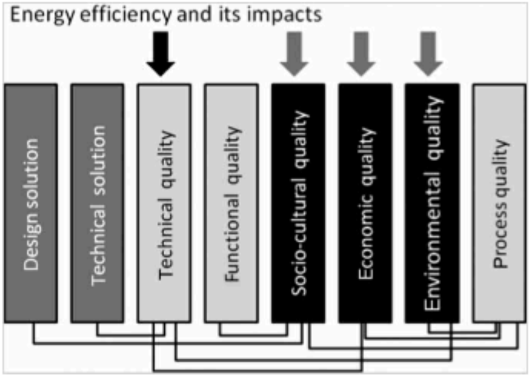

Figure 2. Impacts of energy efficiency on all dimensions of sustainability [35].

Issues relating to the systems themselves in a stricter sense, i.e. issues relating to weighting factors and benchmarks, are not currently being dealt with by standardisation.

2.2 Selected activities

In order to set the scene some related recent projects and initiatives in this field have been researched and will be presented as a short overview here.

2.2.1 LEnSE – FP6: 2006–2008

LEnSE [30] – 'Methodology Development towards a Label for Environmental, Social and Economic Buildings' – was a European research project that responded to the growing need for assessing a building's sustainability. LEnSE developed a methodology for the assessment of the sustainability performance of existing, new and refurbished buildings. The proposed methodology contained a set of 57 sustainability issues, grouped into 11 categories in the three pillars of sustainable construction. The weighting system enabled country-specific setting of weights.

2.2.2 PERFECTION – FP7: 2009–2011

PERFECTION [31] – 'Coordination action for performance indicators for health, comfort and safety of the indoor environment' – additional information available at: http://www.ca-perfection.eu/ – was a European research project with the main objective to develop a

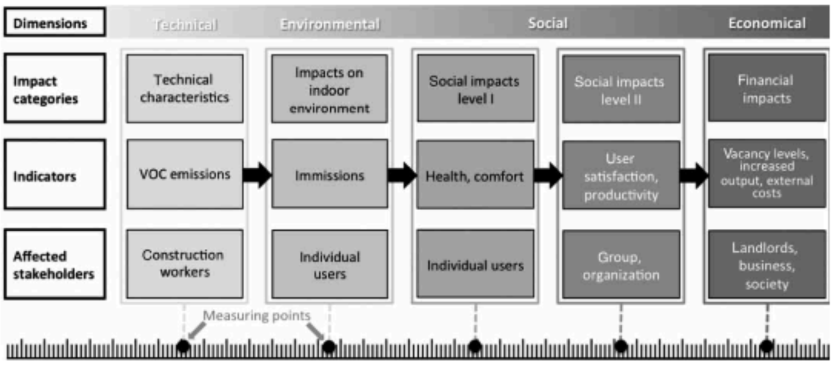

Figure 3. Impact chain - example indoor air quality [35].

framework and a set of indicators concerning the overall quality of the indoor environment of buildings. The main focus is on comfort, health and safety, but also accessibility, positive stimulation of people and sustainability. PERFECTION also developed an online indoor performance rating tool.

2.2.3 *OPENHOUSE – FP7: 2010–2013*

OPENHOUSE [32] – 'Benchmarking and mainstreaming building sustainability in the EU based on transparency and openness (open source and availability) from model to implementation' – is a methodology for assessing the ecological, economic and social performance of buildings in Europe that is being developed by a European consortium of 19 stakeholders for the EU Commission in the Seventh Framework Programme, to show the gaps of the existing assessment methods and to give an overview of minimum standards for sustainable buildings in Europe. The project is on-going and due to end February 2013. See also report [33].

2.2.4 *SuPerBuildings – FP7: 2010–2012*

SuPerBuildings [34] – 'Sustainability and Performance assessment and Benchmarking of Buildings' – is a European research project in the Seventh Framework Programme. SuPerBuildings will develop and select sustainability indicators for buildings (see Figures 2 and 3). The focus is on the development of data validity and reliability of the selected key indicators. It will also develop solutions for the integration of sustainability assessment with building information models and make recommendations for the powerful use of assessment and benchmarking systems as instruments of steering, considering both regulative approaches and economic incentives. The project runs up to the end of 2012. The paper at hand presents selected interim results.

2.2.5 *Sustainable Building Alliance*

The Sustainable Building (SB) Alliance is a not for profit international membership organisation, created in 2008 under the initiative of CSTB and BRE (Building Research Establishment), including certification bodies, research centres, various organisations and key stakeholders of the construction sector. SB Alliance objectives are to accelerate the adoption of sustainable building practices through the promotion of shared methods of building performance assessment and rating. To achieve this, a first set of six common metrics for building assessment was developed in 2009 as a framework to guide the development of performance assessment systems for buildings. The framework does not set targets, as these will need to be set at a national level, but it does provide details of the scope and coverage, in terms of the building life-cycle and indicators, for the following metrics: primary energy, water, greenhouse gas emissions and wastes. Conventions and assessment rules are also defined for the two other issues: thermal comfort and indoor air quality (IAQ). During 2011 and the beginning of 2012, these metrics are being piloted in five European countries. See also report [36]. Additional information is available at www.sballiance.org.

2.2.6 *SBMethod and SBTool*

iiSBE (International Initiative for a Sustainable Build Environment) has always seen itself as a foundation and resource for national and regional systems to adapt and build on. It has further developed its approaches for the so-called SBMethod and SBTool, for the sustainability assessment of buildings, in order to encompass all aspects of sustainability. The SBMethod [37] is a generic framework for rating the sustainable performance of buildings and projects. It may also be thought of as a toolkit that assists local organisations to develop SBTool rating systems.

2.2.7 Developments in European countries

In many European countries methods and systems for the assessment of sustainability of buildings have been developed, piloted and implemented. In certain cases a greater use of LCA and LCC is beginning to emerge. For example the German systems DGNB (Certification System of the German Sustainable Building Council) and BNB[1] (Assessment Systems for Sustainable Building), and SBTool CZ in the Czech Republic systems have been developed [38], which do already comply to a large extend with the requirements of international standardisation, respecting sustainability in its full comprehensiveness.

Additional information is available at:

- DGNB (www.dgnb.de);
- BNB2 (www.nachhaltigesbauen.de);
- SBTool CZ (www.sbtool.cz).

3. Sustainability assessment – re-thinking the structure

A good structure will allow stakeholders to understand an assessment system more easily and in particular allow them to understand their scope for action and for bringing about greater sustainability.

3.1 Object of assessment

The objects to be assessed for the purpose at hand are individual buildings – not neighbourhoods, cities or property portfolios. The whole building is being assessed including the site it stands on. The whole lifecycle, including all energy and mass flows, impacts on the local and global environment, impacts on health, comfort of neighbours as well as that of end-users and visitors, all cash flows and economic consequences are being assessed. Also included are technical and functional qualities of the building, building design and urban design qualities as well as processes relating to planning, construction and operation.

On numerous occasions it has been discussed internationally whether and how far an assessment of the quality of location or the choice of location should enter into a sustainability assessment. Different ways of arguing and approaching this topic are possible. These are influenced by the specific nature and traditions of the planning processes and decision making in different countries. A modular approach is recommended covering the following modules:

- The location;
- The site;
- The building (and its entire life cycle);
- The processes of planning, constructing and operating the building.

In some countries the selection of site and the actual planning of the building present in effect a two-stage process with quite different stakeholders in each phase. This may justify a formal separation of the assessment of the location on the one hand and the assessment of the building on the other. In any case, the assessment of the building should be supplemented by a documentation of information relating to the location. Separating of man-made (infrastructure) and non-man made site conditions may be sensible. If the location is being assessed separately from the building, the site selection process as such may form part of the assessment of management processes during the planning stage.

3.2 Top-down approach

Currently, there are numerous approaches for the preparation and development of systems for assessing the sustainability of buildings. In order to be able to distinguish between these approaches, a typological classification is proposed. For this purpose, a distinction is made between a bottom-up approach and a top-down approach.

Usually, the starting point of a bottom-up approach is the existing indicators and indicator systems. Often these have their base in the areas of resource conservation, as well as environmental and health protection. The indicators are subsequently assigned to the dimensions of sustainability.

A top-down approach is based on the objectives and content of sustainability. First, the dimensions of sustainability are defined. To these areas of protection such as ecosystem and protection goals (e.g. protection of the ecosystem) are assigned. The way and degree of achieving these protection goals must be testable and measurable. Therefore, evaluation criteria are developed, under which specific indicators can be allocated. This method ensures that all aspects/dimensions of sustainability are covered.

Many existing assessment systems face a transition from an approach that is predominantly focused on environment and health issues of buildings. These can be referred to as the first generation of systems with a bottom-up approach. Existing indicator-driven 'bottom-up approaches' often do not cover the full range of sustainability issues. In particular the following problems were found:

- Indicators often do not cover the full range of sustainability issues;
- Indicators may be overlapping;
- Indicators may be of different value in terms of significance.

The need to adapt to emerging standardisation is a powerful driver for existing systems to be developed further, restructured and adapted. Recommendations for this are given in the following.

Using a 'top-down approach' ensures that all current key issues are given due consideration. By covering the full breadth of sustainability issues, the likelihood is increased that all concerns, which various stakeholders have, are covered. It also provides the potential for a feedback loop that allows stakeholders to see clearly what difference to sustainability issues their decisions can make. At the same time the necessary complexity of a sustainability system that implements the key principles of sustainability and all related aspects is being met. The starting point for the development of any assessment system that follows a top-down approach is certain overarching concerns that are being addressed. These concerns are often referred to by the term 'areas of protection' which is commonly found in literature on life cycle assessment (LCA). Alternative terms are 'safeguard subjects' [39] or 'areas of protection' [40,41]. A typical, LCA/ environment-driven definition would be the one used in the Rio Earth Summit declaration [42], which defines 'safeguard subjects' as:

- Biological diversity;
- Human health;
- Production of biomass and fresh water;
- Resource use;
- Aesthetic values.

For use in the context of sustainability assessments this definition has to be modified in order to reflect also the social and cultural, and economic dimensions of sustainability. It ought to be emphasised that setting sustainability goals should not conflict with the artistic freedom of architects and designers. Much rather retaining high quality of design is also seen as a sustainability target (as part of social sustainability).

The authors recommend that the 'areas of protection'[2] should follow the three 'dimensions' of sustainability: the environmental, economic and social dimension. Different stakeholders may have different interpretations of these three dimensions. However, since this is the starting point for all sustainability assessments, a common definition should be determined. At a generic level each dimension can be seen in terms of its intrinsic value and its stability, leading to the following high-level areas of protection:

- Environmental values (e.g. resources, biodiversity, clean air, clean water and soil);
- Stability/health of environment / ecosystem;
- Social and cultural values (including health and comfort);
- Stability of the social systems / social equity;
- Economic values;
- Stability of the economic systems / economic prosperity.

In this context 'value' is the intrinsic merit of a resource or entity. Stability means ensuring that these values will persist long-term, that their state is robust. It is necessary to know the actual value of each subsystem and its stability (in form of trends) to predict its future values. For buildings this means for instance that not only their ability to meet future technical and functional requirements is to be assessed, but also their adaptability to anticipated future regulatory demands regarding environment and health.

The 'areas of protection' in a general sense have to be defined initially from the point of view of the whole of society. They then have to be translated into the terms appropriate to the object to be assessed (here buildings) and adapted accordingly. From the 'areas of protection' certain goals can de deduced.

General goals and those tailored to the object of assessment can be distinguished between. Examples for goals that are related to buildings are:

(1) Environmental goals and resource preservation (energy carriers, raw materials, land, water), i.e. protecting these from over-use and depletion:
  - Protection of ecosystems from negative impacts from emissions and waste products on the local and global environment;
  - Protection of ecosystems from risks;
  - Preservation of biodiversity (flora and fauna).

(2) Social goals
  - Protection of cultural values, ensuring urban and building related design quality;
  - Meeting the needs of users, providing suitable living and working conditions;
  - Safeguarding health and safety of all those involved in the construction stage, providing comfort for the end users.

Aspects frequently discussed here are availability and affordability of housing, however, these are not directly reflected in building characteristics. The same goes for the creation and retention of jobs in the construction and real estate sector. Affordability can in some cases be related to the economic goals. Retention of jobs and related issues can be also seen in economic issues.

(3) Economic goals
  - Optimisation / minimisation of life-cycle costs;
  - Protection of capital, protection of economic value and ensuring stability of value;
  - Reducing external costs.

Impacts on local economy are important, but are not directly reflected in building characteristics.

The way and the extent to which these goals are accounted for or met have to be examined and assessed. Suitable indicators, which may be summarised in entire indicator systems, have to be defined accordingly (see also current ISO and CEN standardisation). These indicators have to be developed with the specifics of the object to be assessed in mind, which is set out in the following paragraphs.

4. Development of assessment criteria and indicators

4.1 Goals and issues as starting points

The process of developing assessment criteria can be explained on the following examples of environmental goals and issues (see Table 1). Where suitable goals have been defined it is necessary to check and measure that they have been adhered to.

To this end indicators based on the measuring of absolute values as well as those based on measuring the 'distance to target' are useful. Goals regarding environmental protection are related to the issues in the right column of Table 1. From these issues specific indicators can then be deduced. For example the issue 'impacts on the global environment' could be reflected in the assessment criteria 'Global Warming Potential'. This principle can be transferred to other environment related goals and issues. For a minimum set of indicators, the current status of international standardisation [22] should be referred to. The authors of this paper have contributed to its development.

5. Stakeholder needs

Having set out a rational framework for structuring sustainability assessments previously, the second driving force for defining an assessment system consists of the requirements that stakeholders have. A survey has been conducted to this end.

5.1 Survey design

Usefulness and effectiveness of sustainability assessments can be influenced especially if the results can influence directly the actions of relevant stakeholders.

To this end relevant stakeholder groups need to be identified and their specific information requirements need to be analysed, so that conclusions regarding content, process and representation of results can be taken into account. The SuPerBuildings surveys were organised in paper and electronic form and were complemented by interviews. Paper surveys were distributed during two sustainable building conferences ('Central Europe towards Sustainable Building' held 30 June – 2 July 2010 in Prague, Czech Republic and 'SB10 Finland: Sustainable Community' held 22–24 September 2010 in Espoo, Finland). During these events 450 paper survey questionnaires were distributed, from which 73 were collected back (return ratio over 16%). In the period of July and September 2010 a call for filling the electronic version of the survey was sent out to the whole project network, resulting in 58 responses. In the same period 21 interviews with local stakeholders around Europe were organised, resulting in filled questionnaires and additional comments. For further details the SuPerBuildings project website can be referred to(see http://cic.vtt.fi/superbuildings).

5.2 Stakeholder groups and their needs

The full potential for positive change, owing to stakeholders understanding their respective spheres of influence, can only be realised fully, if the assessment system meets the needs of all those who come into contact with it.

Valuers and risk analysts for example show increasing interest in sustainability-related information when calculating mortgage values, and project financing risks. Risk-relevant and value-relevant factors are of particular interest. At the moment banks are mainly interested in assessments in the form of a fully aggregated assessment results, but it is known that they also require certain information regarding specific assessment criteria or the underlying project information, in order to use these for their own analysis and their own tools.

Table 1. Interrelation between goals and assessment issues (examples).

Goals	Issues
Preservation of resources from over-use and depletion (energy sources, raw materials, land, water)	- consumption of renewable energy - consumption of non-renewable energy - consumption of biotic raw materials - consumption of abiotic raw materials - consumption of potable water - use / conversion of land
Protection of ecosystems from undesired effects of emissions and waste products on the local and global environment.	- impacts on the global environment - impacts on the local environment
Protection of ecosystems from undesired risks	- risk of harmful ingress of pollutants into air, water and soil
Protection of biodiversity	- protection of biodiversity on site - protection of global biodiversity

Table 2 shows further stakeholders with potential interests in assessment results who have been analysed in terms of their information requirements, due to their respective roles and positions, and specific level of knowledge. It becomes clear that assessment methods and results can play additional roles.

Different stakeholders require different types of information. Some, for example valuation surveyors, want to integrate relevant information into their own tools in order to help their decision-making.

A survey showed therefore a clear preference for partially aggregated results (see Figure 4). Detailed, non-aggregated results of the assessment are most valuable for researchers, academics, architects and designers and manufacturers. Facility managers, planning authorities, authorities (policy makers), clients and users demand partially aggregated results. Fully aggregated results are at the moment the most useful results from point of view of the banking sector, estate agents, insurers and grant providers, community representatives, valuers and end users. However, the authors predict that these groups will also become interested in a number of more detailed results in the medium therm. It is not only important to match the users' needs in terms of aggregation levels of the results, but also to follow their needs by considering how they use the tool. Different stakeholders use the assessment tools for different purposes and at different steps of the process. They have different limitations in terms of time and finances as well as different information requirements. An architect making a choice between several alternatives based on initial sketches clearly has different needs and priorities to those of an investment fund manager looking for a suitable real estate portfolio to invest in. In order to obtain a clearer view regarding the types of uses, part of the project survey was dedicated to this topic (see Figure 5). Academics, researchers, valuers, users of buildings, contractors and clients find a comprehensive assessment tool most useful. Architects and designers and to a degree also property owners want a simple self-assessment tool. Community representatives and planning authorities prefer a short checklist. Third party certification is most suited to valuers, manufacturers, authorities, grant providers, planning authorities and professional associations [43].

Such diverse needs underscore the necessity for a systematic top-down approach, which allows the tackling of the areas of protection at different levels of detail without losing sight of the overall goals of the assessment.

5.3 Consequences for result presentation

Different stakeholders use sustainability assessment systems and their outputs in various ways. Assessment results in particular should be prepared and presented to suit these. Different types of results are:

- Fully aggregated results of the entire assessment (in the shape of a label or certificate);
- Partially aggregated results (results per criteria group, per theme group);
- Assessment results for individual criteria;
- The results for each indicator in terms of the actual (un-assessed) project information.

Results should be provided in a range of aggregation levels:

- Raw building data behind the assessment (e.g. energy consumption in kWh);
- Assessment result aggregated into an indicator level (the value, absolute or relative, achieved for this indicator);
- Aggregated results at indicator group level (the score fulfilled across a sub-group of indicators – e.g. all comfort-related or all energy-related indicators);
- Aggregated results at main group level (the score for each of the main categories: environmental, social, economic, technical and location);
- Results aggregated into one main result or single score.

This topic requires further research as well as the assessment of experiences from practical applications.

6. Recommendations for further development of sustainability assessment systems

Having previously set out key principles for sustainability assessments systems in general terms, these are, in the following, turned into concrete recommendations.

A crucial aim of this paper is to introduce an approach for the structuring of sustainability assessment systems, based on a top-down approach on the one hand and based on the requirements of relevant stakeholders on the other. The authors intend for these recommendations to help in particular the development of new systems or the further development of existing systems. The proposed structure has been presented in Figure 6. This paper concentrates on the integrity of the conceptual framework of sustainability assessments, leading to the following general recommendations.

The following process is being proposed:

(a) Striving towards a more precise definition of sustainability

The translation of principles for sustainable development requires a targeted discussion of the interdependencies and reciprocal effects of social, economic developments, while at the same time taking into account environmental

Table 2. Purpose of assessment systems and stakeholder needs.

Purpose	Stakeholder	fully aggregated results	partially aggregated results	assessment results for indiv. indicators	actual project information
as a basis to communicate the aims and objectives regarding the project	clients designers specialist consultants project managers planning authorities (local authorities)		X		
as a checklist for designers	designers specialist consultants			X	X
as basis for informing other third parties	estate agents banks	X	X		X
as basis for informing third parties - surveyors in particular	valuation surveyors	X	X	X	X
as a selling point in a competitive market	buyers tenants	X		X	
as an indicator for corporate social responsibility and information source for relevant reporting	senior managers	X	X		
as a tool in the tender process in 'green procurement'	procurers (in particular in public procurement)	X		X	
as a tool for quality assurance in 'green procurement' (in particular public procurement)	procurers (in particular in public procurement)			X	

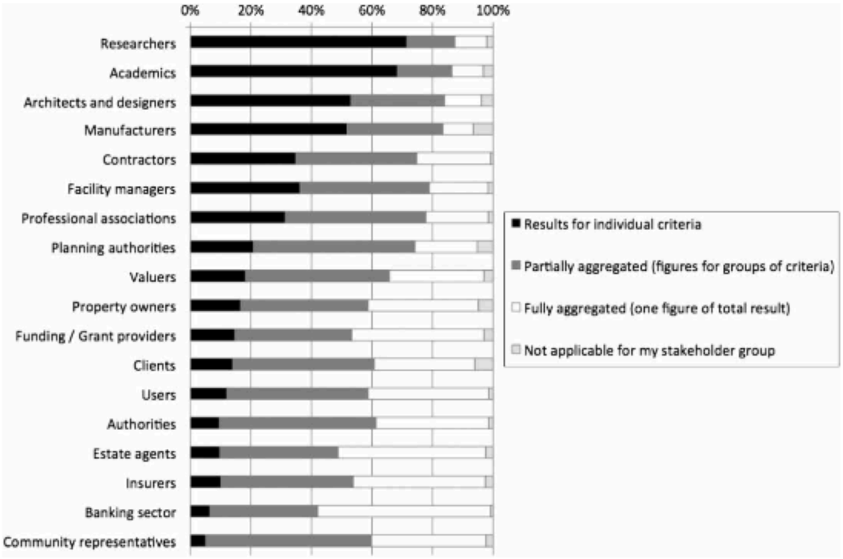

Figure 4. Preferences on aggregation levels [Hájek and Lupíšek, 2010].

protection and preservation of resources. This requires the consideration of environmental and social, as well as the economic, dimension of sustainability. Already at this point fundamental decisions are being made. A decision is being made whether the notions of strong or weak sustainability are being followed [44]. At the same time the question arises as to what weight is being attributed to environmental issues in relation to social and economic issues. From the point of view of the authors this is a political decision to be made.

It is recommended that as part of the dimension of sustainability the relevant areas of protection are defined. This would be analogous to LCA practices (where the terms 'areas of protection' or 'safeguard subjects' can be found in literature). In the context of an assessment these can then serve as 'end-points' [45].

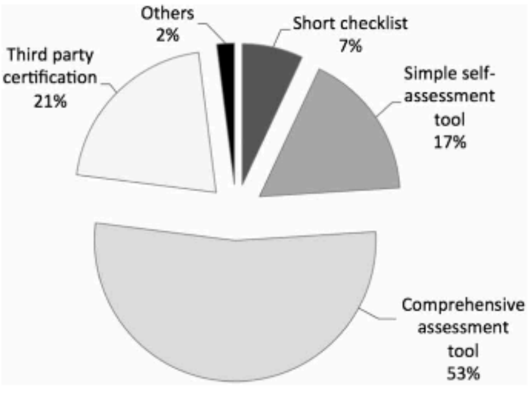

Figure 5. Demand for different types of tools [Hájek and Lupíšek, 2010].

(b) Specifying overarching goals

Goals can be deduced from the areas of protection. The way and the extent to which these goals are being met can be assessed. The goals therefore provide the foundation of the assessment criteria and assessment scales to be developed.

The steps a) and b) represent very general principles for the development of systems. Since they originate from the areas of protection and related goals (top-down approach), it is ascertained that the full breadth of sustainability issues are being covered, but also that they are in line with the general principles and management practices for sustainable development. However, this general approach has to become more specific as it is adapted to the object of assessment (in this case buildings).

(c) Adaptation to the object of assessment

A step is necessary, where the general principles listed above, that are true for any type of sustainability assessment, are made more specific and adapted to the specific object to be assessed. In this case the object to be assessed is the building and the site it stands on, as these are physically connected and for the purpose of a sustainability assessment closely interdependent. One important aspect in this context is the definition of the functional equivalent. Furthermore it has to be ascertained, that the information required for the

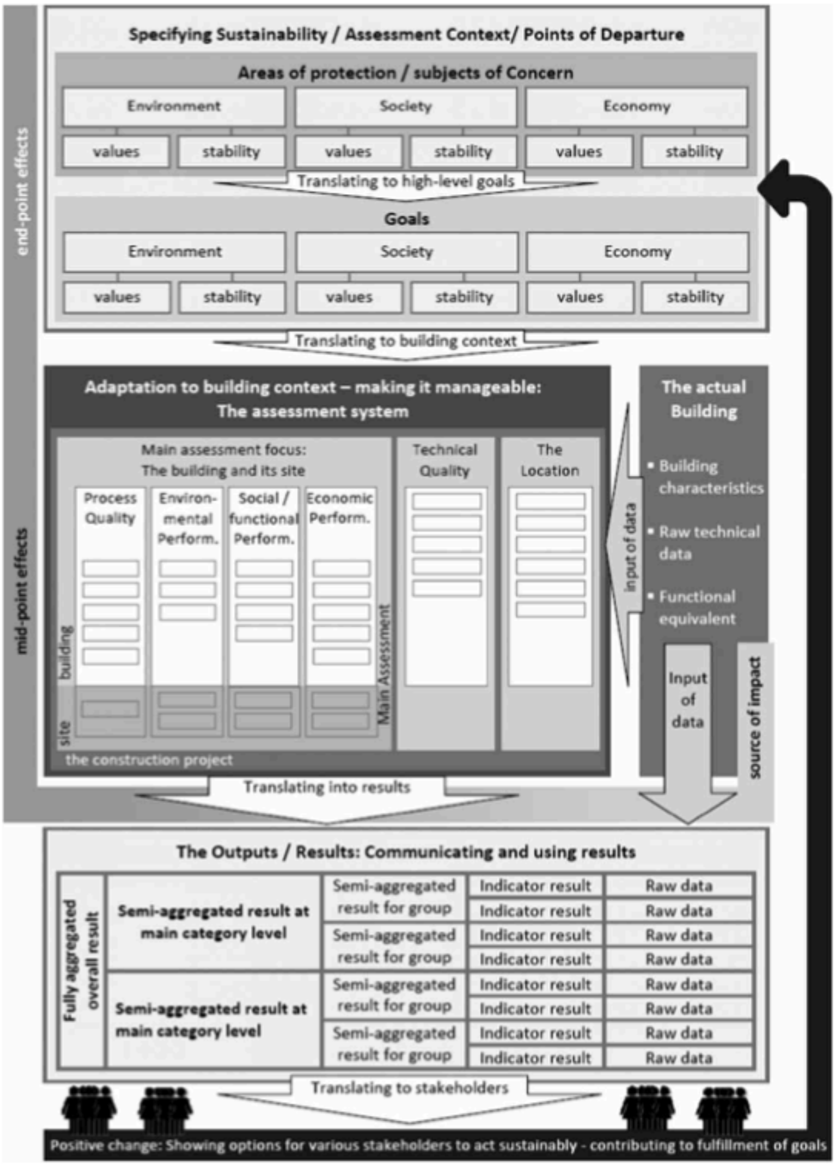

Figure 6. SuPerBuildings system structure and context [Lützkendorf and Immendörfer, 2010].

assessment is at all obtainable, in so far as there are interdependencies between available information and the nature of the assessment. (Environmental aspects can only be assessed using LCA, if LCA-data sets are readily available).

(d) Development of a structure of assessment criteria

In accordance with the requirements of the object of assessment (i.e. the building and plot) an appropriate structure for the sub-sets of assessment criteria needs to be found. Weights of sub-sets of criteria in relation to others are once again a political decision. When groups of criteria are weighted internally, weighting factors can be based on principles of their scientific relationships. It is recommended that in the interest of a modular structure the characteristics and qualities of the location are captured in a separate module, the same applies to technical qualities.

For the other groups of criteria key consideration should be given to distinguish between criteria relating to the building and site and between criteria relating to physical building characteristics and those relating to processes.

Treating the qualities of planning processes, construction processes and the operation separately can help motivate those parties involved in these processes, leading to an improvement in the quality of their work. On the other hand, it ascertains that these processes are not treated at the same level as those relating to the physical building and plot (energy monitoring and targeting is not necessarily an indicator for the energy efficiency of the building).

Assessing the qualities of the planning and construction processes and building related social aspects in isolation is difficult, as these can hardly be separated from the functional qualities of the building. It is therefore proposed to combine these aspects into one group.

The groups of assessment criteria can be ordered logically. The environmental quality can be subdivided into global, regional, local and site-specific aspects.

Social sustainability issues can be broken down further into aspects relating to individuals, groups (e.g. tenant groups), neighbourhoods, the local community, society at large and furthermore also those groups involved in the production, construction and operation of the building. Economic sustainability issues can be subdivided into those relating to the end user perspective, those relating to the owner, those of the local community and again, those of society at large.

Individual assessment criteria will not be presented here but readers are referred to ISO 21929-1 [22]. It is however important to point out that indicators that are to be used have to be truly appropriate for new buildings or respectively for existing buildings (by for example assessing energy demand for the former, but energy consumption for the latter, predicted mean vote (PMV) for the former but actual measured user satisfaction for the latter). The consequences of choosing the multiple effect approach for the system structure need to be studied further.

(e) Assessment results and presentation of results

In accordance with the requirements of the different target groups (see also section 4) assessment results must not only be given as fully aggregated results. Detailed results for individual indicators must also be provided. Especially, where weighting factors are being used, their use must be made transparent and comprehensible. In the interest of future repeat-assessment of a building and in the interest of third parties using an assessment as a resource for building information, raw data must also be made available in addition to the assessed data.

(f) Using assessment results to support decision-making processes

The ultimate aim of sustainability assessments is to actively support stakeholders in their decision making processes or alternatively, to passively influence their decisions. There is the potential for a crucial feedback loop in as far as such decisions can contribute to the achieving of the strategic goals relating to the areas of protection. The stakeholders involved can therefore become more aware of the influence they have in implementing sustainable development.

As a result, sustainability assessments are no longer mere marketing instruments. They can serve as sources of information for due diligence, for portfolio analysis, for valuations and for rental or sales decisions. The process of the assessment in itself supports the formulation of agreements on goals as well as quality control and quality assurance. A resulting added value can increase the demand for sustainability assessments. Ultimately, sustainability assessments will become part of holistic approach to decision making, by showing in each of the situations mentioned above, how the overarching areas of protection can be influenced by system users.

7. Summary

This paper presents a range of proposals for the further development of sustainability assessment systems. It is hoped that these recommendations may lead to the positive outcome of systems moving closer in terms of their content, allowing for better comparability, without however, questioning the autonomy of these systems. A top-down approach is recommended, which deduces the system structure and indicators from the areas of protection and shows system users the influence they have on these. Greater alignment of assessment systems with standardisation is also required.

In this context crucial issues are the treatment of multiple effects and (related to it) the safeguarding of validity of indicators. Initial outcomes regarding these issues have been presented. Further research is required and expected to emerge from the current EU-project SuPerBuildings in due course. Project results can be found at http://cic.vtt.fi/superbuildings.

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Notes

1. DGNB and BNB are based on the same methodology. BNB has been specifically adapted to the needs of the public sector and is now obligatory for all new buildings of the German Federal Government. DGNB cooperates with numerous partners worldwide.
2. The term 'areas of protection' is used in this paper, as this is commonly used in literature on LCA. The term is found to be problematic by native English speakers, as it has been clearly coined by non-native speakers, nevertheless it is common in literature. Other terms used synonymously are 'safeguard subjects', 'areas of concern', or 'impact areas'.

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Design strategies for buildings with low embodied energy
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Design strategies for buildings with low embodied energy

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This paper presents building design strategies for reducing embodied energy and embodied carbon dioxide emissions as developed within the International Energy Agency's Energy in Buildings and Communities Programme. The design strategies are illustrated using three case studies of design optimisations of building elements, the building structural system and the whole building. The first case study shows the environmental optimisation of a curtain wall facade element using bio-based materials. The second case study presents the optimisation of the structural system for a residential building by lightening the floor structures through utilising ultrahigh-performance concrete and vertical elements with reduced cross-section. The third case study presents an alternative design for a passive-design family house in Prague in the Czech Republic, leading to hybrid construction of light prefabricated concrete elements, a timber frame and a timber-based building envelope.

1. Introduction

In the last several years, European countries have significantly improved the standards and legislation related to the energy performance of new buildings (EPEC, 2009). Part of the life cycle of a building considers the environmental impacts and resource use of the operational stage of a building's life (modules B1 to B7 according to BS EN 15978:2011 (BSI, 2011)), but this stage has now become a less significant contributor with respect to the entire life cycle given the improved environmental efficiencies of both new and refurbished buildings. However, the impact of the product stage and the construction process stage (modules A1 to A5 according to BS EN 15978:2011 (BSI, 2011)) in the entire life cycle is now proportionally larger (Vonka, 2006; Vukotic *et al.*, 2010). This realisation has led various researchers to investigate embodied energy (EE) and embodied greenhouse gas (GHG) emissions in buildings more deeply (Ibn-Mohammed *et al.*, 2013; Rennie, 2011) and to use the amount of EE or embodied carbon dioxide equivalents (EC) as a key design optimisation indicator (e.g. Knight and Addis, 2011; Moncaster and Symons, 2013). These indicators are also now becoming included in building sustainability assessment schemes (e.g. Mateus and Bragança, 2011; Vonka *et al.*, 2010). The stages where energy and carbon dioxide emissions become embodied into buildings have been studied within Annex 57 of the International Energy Agency's (IEA) Energy in Buildings and Communities (EBC) Programme (hereafter referred to as Annex 57). Annex 57 has formulated a set of design strategies for reducing the levels of EE and EC. These design strategies are discussed and exemplified in this paper.

1.1 Objectives

The main objectives of this paper are (*a*) to introduce design strategies for reducing the levels of EE and EC, (*b*) to present the application of these strategies to case studies from the Czech Republic and (*c*) to evaluate the achieved environmental benefits in comparison with business-as-usual designs.

2. Background

2.1 IEA EBC Annex 57

The IEA is running a programme known as Energy in Buildings and Communities, which is currently supporting 15 projects or so-called Annexes (IEA, 2016a). One such project, which started in 2011 and which has been led by Utsunomiya University, Japan, is Annex 57, entitled Evaluation of Embodied Energy and Carbon Dioxide Emissions for Building Construction. The main objectives of Annex 57 are (*a*) to collect existing research results concerning EE and EC emissions due to building construction, to analyse the results and to summarise them into the state of the art; (*b*) to develop guidelines for the methods for evaluating the EE and EC equivalent emissions associated with building construction; and (*c*) to develop guidelines for the measures for designing and constructing buildings with lower levels of EE and EC (IEA, 2016b). The present paper is focused on the third objective and describes some examples of strategies developed for the reduction of EE and EC emissions.

3. Design strategies for the reduction of EE and EC

The work within Annex 57 was divided into five subtasks (STs): ST1, basics; ST2, literature survey; ST3, evaluation methods for EE and EC; ST4, design and construction methods for buildings with low EE and low EC; and ST5, overall research plan, publication and dissemination.

The need to formulate design strategies for reducing the levels of EE and EC equivalent emissions in buildings arose from the recognition that these core sustainability issues are becoming more important in the building design process, particularly in the early stages of the process. Each architect must address these issues properly in his/her own workflow. Sometimes, the approach is one of coordinated action of the whole design team, but more commonly the effort is driven just by intuition, leading to mixed results. This fact was one of the main motivations for the initiation of Annex 57.

The ST4 team drafted the strategy in four steps

- reducing the overall consumption of materials throughout the entire life cycle
- substituting conventional materials with alternatives with lower environmental impacts
- reducing the impact of the construction stage
- designing for a low-impact end-of-life stage.

The team for ST4 gathered more than 90 life cycle assessment (LCA)-based case studies and conducted an extensive analysis of these case studies, aimed at identifying effective approaches to the reduction of EC emissions and EE and their generalisation into formulated strategies (IEA, 2016c).

3.1 Strategy 1: reduction of the overall consumption of materials throughout the entire life cycle

The strategy of reducing the consumption of materials was further divided into six sub-items

- 1.A: reuse of building structures
- 1.B: optimisation of building form and layout plan
- 1.C: flexible and adaptable design
- 1.D: lightweight constructions
- 1.E: low-maintenance design
- 1.F: components' service life optimisation.

Strategy 1.A proposes reusing the existing building or integrating existing building elements into the new design before starting the completely new construction. Strategy 1.B focuses on the precision of the spatial arrangement of the layout in line with the intended purpose of a building, which can lead to a reduced built volume of the building and thereby reduce the use of primary materials. Strategy 1.C proposes that the design team look into the future and design building elements and spaces in a way that easily enables future adaptations to be made to the building, including modifying it or completely changing its use, without the need to rebuild or to build a completely new building for the intended change in use. Strategy 1.D aims at the possible reduction in the use of building materials as a result of optimised orientation, span and shape of the building as well as the properties of the materials used. Strategy 1.E, low-maintenance design, encourages architects to prefer simple (and thus low-maintenance) surfaces and verified details to reduce the future amounts of materials needed to maintain structures or replace elements when deterioration or malfunction occurs. Strategy 1.F serves as a reminder to design teams to optimise the service life of used components, which should result in the design of high-quality components with longer expected service lives, or in the combining of sets of components with similar expected service lives (e.g. a set of building technology components that can be replaced together in a single step), as well as allowing easy access to and replacement of those building components that have shorter service lives compared with the surrounding components and/or structures.

3.2 Strategy 2: substitution of conventional materials with alternatives with lower environmental impacts

The strategy substituting conventional materials with alternatives includes three sub-items

- 2.A: the utilisation of recycled materials
- 2.B: substitution with bio-based and raw materials
- 2.C: the use of innovative materials and technologies with lower environmental impacts.

Strategy 2.A encourages the use of recycled materials instead of new materials as much as possible. Strategy 2.B proposes to utilise bio-based materials derived from sustainably managed sources and raw materials, as these usually have lower EE levels and lower carbon dioxide footprints compared with manufactured materials. Strategy 2.C promotes the use of innovative materials and technologies as possible replacements for existing solutions (when the environmental burden is proved to be lower than that of conventional materials).

3.3 Strategy 3: reduction of construction stage impact

The construction stage is associated with EE and EC derived from transporting materials from the factory to the construction site (module A4 according to BS EN 15978:2011 (BSI, 2011)) as well as from the installation process (module A5 according to BS EN 15978:2011 (BSI, 2011)). The installation process does not usually make a significant contribution to the overall impact of the life cycle of the building (Zhang *et al.*, 2013) although, in some cases, the transportation impact is sufficiently large to necessitate consideration. It is recommended that local materials should be used to avoid the high EE and EC of this stage and to reduce energy consumption during construction.

3.4 Strategy 4: designing for a low-impact end-of-life stage

This strategy proposes to ease the future reuse of building elements by applying a design for disassembly approach and using materials that are recyclable using present technologies, both of which should lead to potential future reductions in EE and EC.

4. Methodology

The research approach of this paper is to take three case studies of environmental optimisation and indicate which of the earlier mentioned design strategies were used in the optimisations. The benefits of the optimisation in each case study are then analysed with the aim of developing conclusions on the potential benefits of applying the utilised design strategies in a more general way.

5. Case studies

In this paper, the mentioned design strategies are applied to building elements (case study 1, or CS1), to the building structural system (CS2) and to the whole building (CS3) (Table 1).

5.1 CS1: the design of curtain wall facade elements using bio-based materials

5.1.1 Case study description

The research project in the Czech Republic termed ‘Intelligent Buildings’ focused on developing a new environmentally friendly curtain wall system (CWS) for deep renovations of existing buildings and for new buildings at a nearly zero-energy standard (Tywoniak *et al*., 2014a, 2014b). The main motivation for the development of the new-generation CWS was a market demand for an environmentally friendly solution for replacing original aluminium and glass-based CWSs used in central European buildings between the 1960s and the 1980s and which are now coming to the end of their service lives. In a typical retrofit scenario, the old CWS is replaced with a modern metallic CWS that is usually based on aluminium or steel structural elements. The subject of optimisation in the present study is a typical replacement for a single wall panel with a height of 3·3 m and a width of 1·5 m with an integrated window (position 05 in Figure 1).

The main design prerequisite to ensure the market uptake of the new CWS system was to have a competitive price and to match or surpass the key technical parameters of present standard metallic CWSs available on the market while also having lower environmental impact and comparable or better thermal properties. The key parameters were requirements for *U* values, limited thermal bridges, watertightness and airtightness, fire resistance and improved values of environmental indicators based on LCA. As the new CWS was intended for nearly zero-energy buildings, there were additional defined requirements for the possible integration of both external venetian blinds to prevent summer overheating and renewable energy sources onto the facade. As buildings for education was one of the main target typologies, there was also a requirement for the very fast replacement of the obsolete CWS by the new system.

5.1.2 CS1: application of design strategies and the resulting design

The main strategy used in the design process was strategy 2.B: the substitution of existing materials with bio-based and raw materials.

The core requirements for the environmental properties of the CWS were

- over 50% of the mass should consist of renewable materials
- minimal use of materials with high environmental impacts (e.g. metals)
- lower environmental impacts in comparison with those of conventional CWSs
- maximum utilisation of local materials (produced in the country)
- the CWS production technology should generate minimum waste
- easy maintenance
- dismantling and recyclability of the CWS should be as simple as possible.

	Subject	Design stage	Applied design strategies
CS1	Curtain wall facade elements using bio-based materials	Building elements	■ Substitution for bio-based materials ■ Use of innovative materials with lower environmental impacts ■ Reduction of construction stage impact ■ Design for low impact of end-of-life stage
CS2	Lightweight structural system based on advanced silicate materials and recycled materials	Structural system	■ Lightweight constructions ■ Utilisation of recycled materials ■ Use of innovative materials with lower environmental impacts
CS3	Family house with hybrid timber and concrete structures	Whole building	■ Flexible and adaptable design ■ Lightweight constructions ■ Substitution for bio-based materials

Table 1. Overview of presented case studies

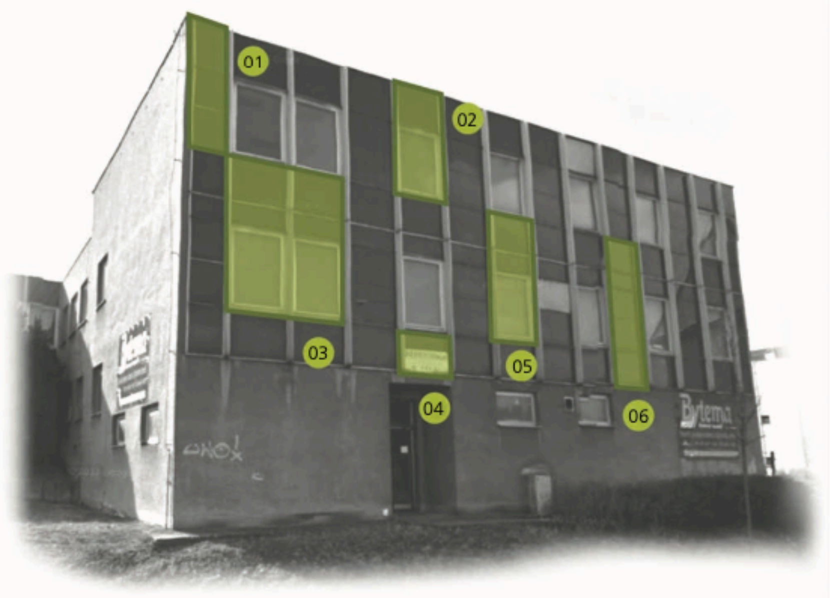

Figure 1. Schematic drawing of CWS panel types on a building due for renovation. The panel in position 05 was the subject of optimisation in CS1. Source: Bureš *et al.* (2015)

The structural elements of the designed panel were designed using laminated veneer lumber. Panelling is made of oriented strand boards, window frames are constructed of wood and external window cladding uses thermally treated wood. Thermal insulation consists of wood fibre and cork (see the visualisation of panel composition in Figure 2). The resulting new CWS panel contains 93% by weight wood-based materials in its opaque variant and 65% in its transparent variant. Some of the listed materials also apply to strategy 2.C: the use of innovative materials with lower environmental impact. With respect to this strategy, laminated veneer lumber is a stable and modern bio-based material that allows very precise machining and which has a relatively high bearing capacity. The use of this material enables a significant reduction to be made in the dimensions of elements (compared with standard timber). In addition, thermally treated wood is a low-maintenance material that is much more durable than standard timber.

Strategy 3, reducing the construction site impact, was also applied. The final design includes a high level of prefabrication and eliminates the need for scaffolding use on site, which significantly reduces installation time. Strategy 4, designing for a low-impact end-of-life stage, is addressed through the anchoring system of the panels, which enables easy future disassembly (Figure 3).

To check compliance with the requirements, the designed CWS was prototyped and underwent extensive testing of its technical properties in accredited laboratories (airtightness and watertightness, acoustic performance, full-scale fire resistance tests) and in the authors' laboratories at the University Centre for Energy Efficient Buildings (UCEEB) of the Czech Technical University in Prague (double climatic chambers, long-term testing in real conditions) (Figures 4 and 5).

5.1.3 CS1: assessment methodology

A simplified LCA comparing a panel of the new CWS with a conventional aluminium panel of similar size and thermal transmittance was conducted to evaluate the environmental benefits of the new CWS panel.

5.1.3.1 BOUNDARY CONDITIONS

The functional unit is one CWS panel with a height of 3·3 m and a width of 1·5 m with an integrated transparent part (window: 1·8 m^2) and thermal performance expressed by a thermal transmittance of $U = 0{\cdot}57$ W/(m^2 K).

A service life of 30 years was considered for both alternatives and with no replacement of materials during the service life.

The reference flow was defined as the mass of construction materials needed to create a functional unit with a service life of 30 years. Data for individual materials in the windows were used because of the lack of inventory data for window assemblies.

Figure 2. Visualisation of designed CWS panel from CS1

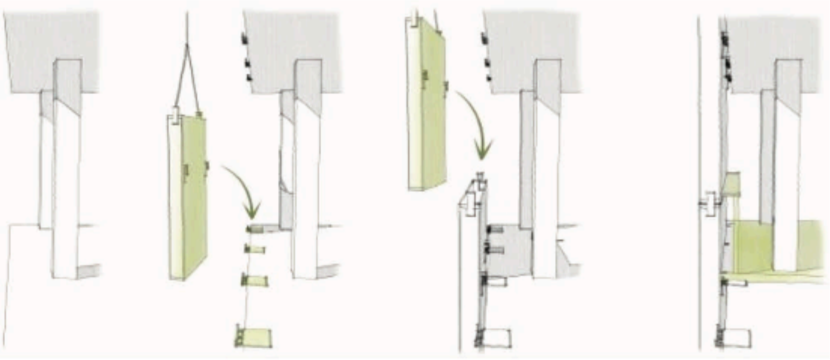

Figure 3. Visualisation of CWS installation (CS1)

Figure 4. Long-term testing of sample panel from CS1 (variant with integrated photovoltaic panels). (a) Installation of sensors; (b) assembly on site; (c) the final look of panels in the tested facade. Sources: Lupíšek *et al.* (2015) for (a) and (b) and Monika Žitníková of UCEEB for (c)

The system boundary was cradle-to-gate (modules A1 to A3 according to BSI (2011) were included).

Environmental data for construction products were taken from German environmental product declarations (EPDs) (German EPDs are up to date and specific to actual construction products, and German and Czech construction market and production technologies are similar). The selection was made according to the best-matched building materials used in the panels of the CWS and the technologies described in EPDs.

Several assumptions were made considering LCA data quality.

- Time-related representativeness: German EPDs are new and specific to actual building products.

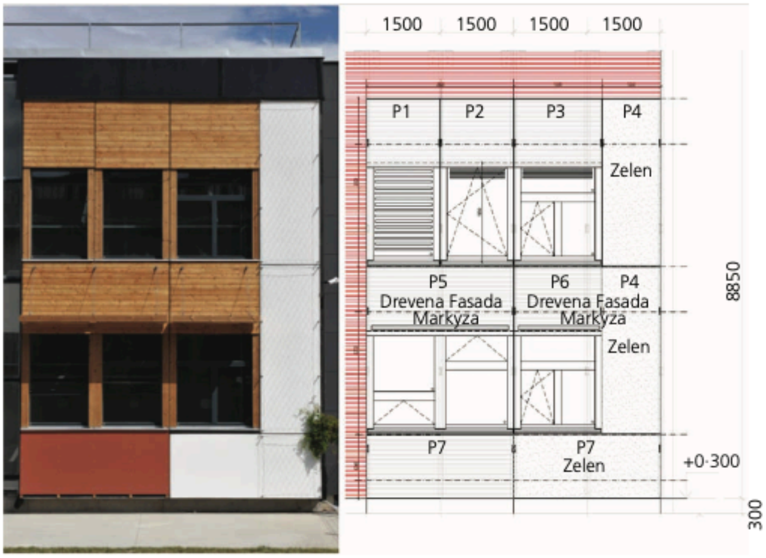

Figure 5. Photograph and schematic illustration of designed CWS from CS1 pilot installation on the south facade of the UCEEB, Czech Technical University, Prague. Source: Tywoniak *et al.* (2015)

- Geographical representativeness: the German market is very close to the Czech market. The electricity mix is closer than the Swiss one, for example (another option was to use the Ecoinvent database (Ecoinvent, 2016)). Furthermore, the data from German EPDs are considered to be highly consistent and plausible according to the same product category rules used for calculations and the unified system of Institut Bauen und Umwelt.
- Technological representativeness: production technologies were assumed to be similar.

By applying cutoff rules, ancillary materials were excluded.

The assembly processes of the final CWS panel were not included, as they consisted mainly of manual work, or no data were available.

5.1.3.2 LIFE CYCLE ASSESSMENT

During the impact assessment step, environmental impacts were calculated on the basis of reference flows for both curtain wall alternatives and the selected environmental indicators: global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP) and total use of non-renewable primary energy resources (PEI_{nre}). The set of indicators was selected according to the Czech national building sustainability certification scheme SBToolCZ (Vonka *et al.*, 2013) so that the results of LCA could be further used for certification.

5.1.4 CS1: results

The results of the interpretation stage of the comparative LCA are summarised in Table 2 and displayed in Figure 6. It is evident that the wood-based CWS panel caused lower impacts in all six environmental parameters. The large difference in GWP is caused mainly by the amount of biogenic carbon dioxide embodied in the wood-based materials, which is included in the LCA calculations according to the product category rules. This issue makes a big difference and depends on the LCA methodology; however, the authors' team supports this approach.

The only indicator that is almost the same for both variants is the ODP. The reason for such a result may be that ODP values are generally very low for all building materials, as the main chlorofluorocarbon and hydrofluorocarbon pollutants are forbidden in the production processes. However, as the relevant life cycle inventory data were not available during the LCA, other possible reasons may also apply.

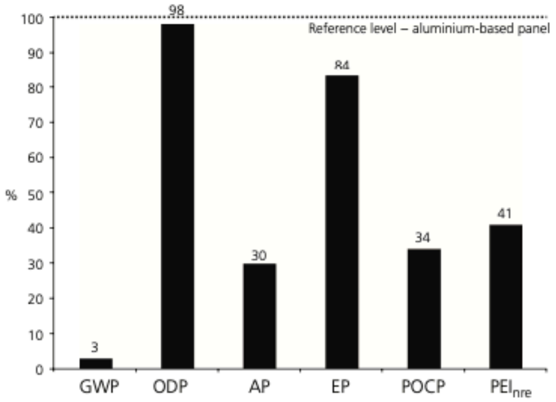

Figure 6. Results of a cradle-to-gate analysis: a comparison of the cradle-to-gate environmental impacts of a wood-based CWS panel (CS1) with an aluminium-based CWS panel with similar *U* values and service lives. The reference level (100%) represents the environmental impacts of an aluminium-based CWS panel. The numbers above the bars (in per cent) show the ratio of the environmental impacts of a new wood-based CWS panel to those of an aluminium-based CWS panel

It was very important to find the main critical point in the environmental performance of the CWS during its development. Therefore, the contributions of different materials to the overall impacts of the CWS were examined. Regarding the wood-based CWS variant, the highest impacts were associated with the wooden materials, which is expected as their mass percentage in the CWS panel is 65%. The impacts of the aluminium and steel parts were very high (43% in the case of AP and 23% in the case of PEI_{nre}), despite their combined mass being only 7% of the total.

An interesting result was the non-renewable energy indicator, which had similar values for the two CWS variants. The largest

Curtain wall type	GWP: $kgCO_2e$	ODP: kg chlorofluorocarbon-11 eq.	AP: kg sulfur dioxide (SO_2) eq.	EP: kg phosphate (PO_4^{3-}) eq.	POCP: kg ethene eq.	PEI_{nre}: MJ
Wood	25·1	$2{\cdot}36 \times 10^{-5}$	1·976	0·6538	0·1291	4765·2
Aluminium	830·4	$2{\cdot}40 \times 10^{-5}$	6·582	0·7828	0·3764	11 634·8

$kgCO_2e$, kilograms carbon dioxide equivalent; eq., equivalent

Table 2. Results of simplified comparative LCA of wood-based curtain wall panel and aluminium-based curtain wall panel (4·95 m^2, including 1·8 m^2 window)

part of PEI_{nre} in the case of the aluminium-based variant is contributed by the aluminium parts. The reason for this is probably the high proportion of hydroelectric power used for aluminium production, but because of the unavailability of life cycle inventory data, the reason for such a high renewable energy value remains unverified.

Overall, all the environmental indicators of the wood-based CWS are lower compared with those of the aluminium-based variant; thus, the wood-based CWS has better environmental performance. Therefore, the objective of creating a structure that is more environmentally friendly than the conventional aluminium-based CWSs was attained. The method of applying strategy 2.B showed its benefits.

However, there is still scope to improve the environmental performance during further development of the product. The potential lies in optimising and simplifying the complex shape by reducing the number of components.

5.2 CS2: lightweight structural system based on advanced silicate materials

5.2.1 CS2: case study description

The subject of this case study is a general structural system of a small six-storey house with a ground plan of around 10 m × 20 m that can be used as a residential or office building (see drawings in Figures 7 and 8). The house is designed with a universal layout enabling the inclusion of many feasible structural and material alternatives. The layout of the building is intentionally not just rectangular to allow architectural flexibility. The typical structural system for such use would be typically made as a concrete skeleton consisting of full concrete floor slabs (230 mm thick) and squared columns (350 mm × 350 mm in cross-section). This is the reference scenario, termed ‘V0’ (Figure 9).

5.2.2 CS2: application of design strategies and resulting design

The case study presents a combined approach using strategy 1.D (lightening of the structural system), strategy 2.A (the utilisation of recycled materials) (Hájek *et al*., 2014) and strategy 2.C (the use of innovative materials with lower environmental impacts). In the first step, variant 1 (V1) was designed (see Figure 9) with features of standard ‘lightening’ of concrete structures: the full reinforced concrete (RC) floor slabs were replaced by prefabricated hollow panels (250 mm high), which enabled the dimensions of the load-bearing concrete columns to be reduced to 300 mm × 300 mm (a reduction of 27% in cross-sectional area). In the next step (V2), floor panels with a height of 250 mm were designed with ultra-high-performance concrete (UHPC) lightened by lightening elements (a mixture of waste wood shavings and cement) (Figures 9 and 10). The columns were also redesigned: the lowered weight of floor slabs and the utilisation of UHPC enabled a design of column cross-section of just 200 mm × 250 mm with an additional gutter on one side, which can be further used for thermal insulation, piping or cabling ducts (a reduction of 68% in cross-sectional area compared with the columns of V0).

5.2.3 CS2: assessment methodology

The detailed LCAs of V0, V1 and V2 were made with the following assumptions

- V0: reference monolithic RC frame structure made of concrete C30/37 with column dimensions of 350 mm × 350 mm, girders of 350 mm × 500 mm and monolithic floor slab with a thickness of 230 mm, with main reinforcement in one direction.
- V1: precast RC frame structure made of concrete C30/37 with column dimensions of 300 mm × 300 mm, precast girders of 300 mm × 450 mm and hollow core panels with a thickness of 250 mm.
- V2: optimised high-performance concrete (HPC) frame structure made of concrete C100/115 with columns with reduced cross-sectional girder dimensions of 200 mm × 400 mm and floor structure panels as shown in Figure 9. Floor panels are lightened by lightening elements from wood shavings concrete, and the HPC parts are reinforced with dispersed steel microfibres amounting to 80 kg/m^3 fresh concrete (1% vol.).

The functional unit constitutes the whole structural system of a six-storey residential or office building (Figure 8). The analysis was focused primarily on load-bearing structures (building envelope, partitions and surface finishes were excluded as they can be identical in all variants). In the following analysis, an expected life span of 100 years for the frame structures was considered for all alternatives. The reference flow was defined as the mass of construction materials needed for the creation of a functional unit and its end-of-life treatment. The construction phase of the life cycle covers the production of cement, aggregates and admixtures; transport of the raw material to the concrete plant; concrete production with respect to production technology (precast or monolithic); pumping of fresh concrete; formwork; and transport to the building site (crane). Wood shavings are considered as a waste product; therefore, only energy for transporting wood shavings to the concrete plant is considered in the analysis. The end-of-life phase calculates the amount of waste from demolition, the number of demountable components that can be reused and the related transport. Environmental data were taken from Concrete_LCA$^{\text{Tool CZ}}$, a database of regionally available materials based on data provided by companies producing and/or selling their products mainly in the Czech market (Fiala, 2011).

5.2.4 CS2: results

Figure 11 presents a comparison of the assessed alternatives. A reference level of 100 was given to V0 (a monolithic RC frame structure of C30/37 concrete), which has the highest environmental impacts in all the assessed criteria. The V1 alternative (precast RC frame with hollow core precast slabs) showed a reduction of 30% in the consumption of raw materials compared with V0, and the lightened structure of V2 showed a further 24% reduction. V2 represents the highest reductions in all

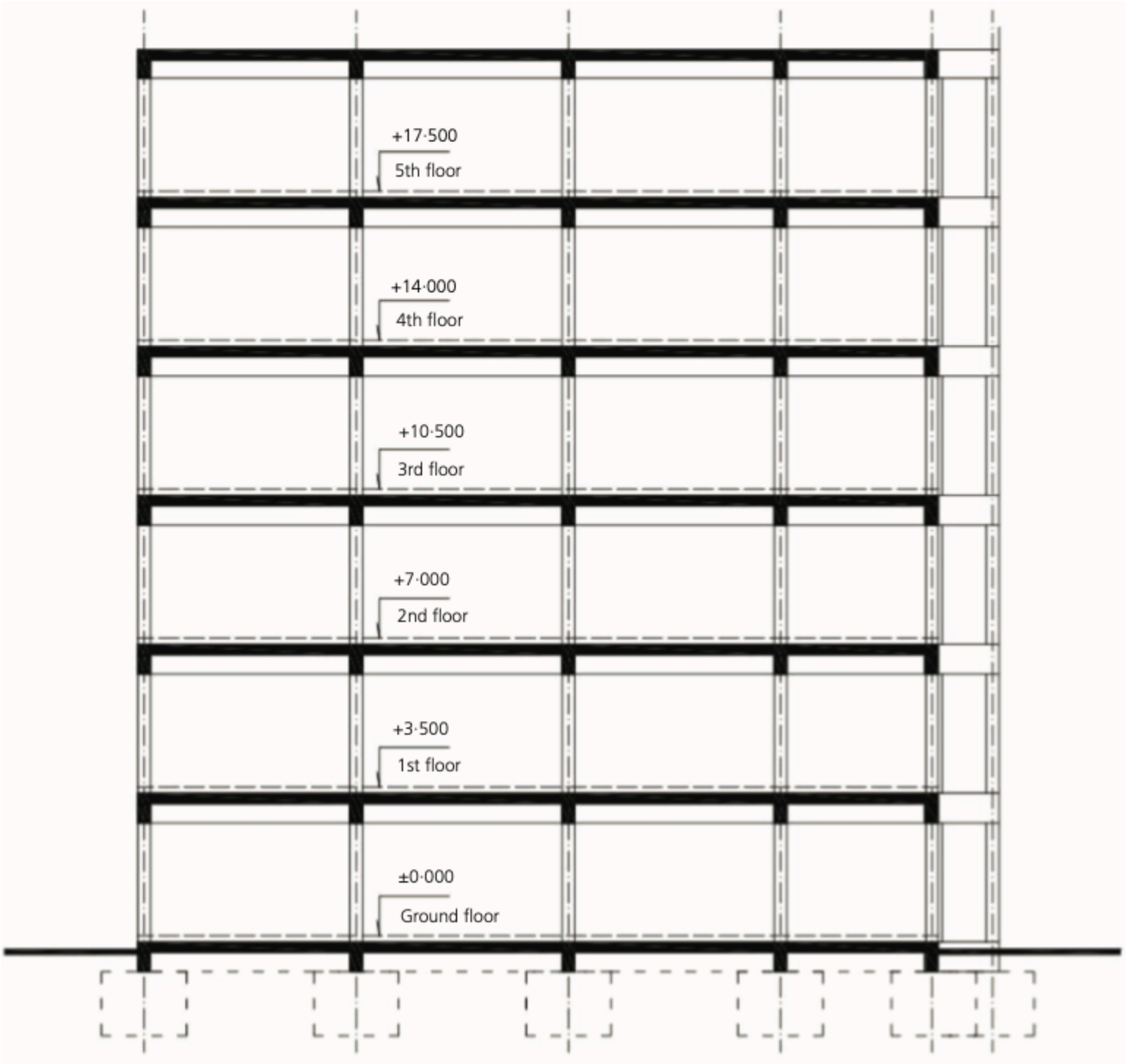

Figure 7. Section of the subject of CS2 – a six-storey residential or office building (dimensions in m)

the assessed environmental criteria except for water consumption (because of the high water absorption of lightening elements from wood shavings concrete). The reduction in the environmental impacts of V2 ranged from 10 to 54% compared with V0 and from 2 to 24% compared with V1 (see Figure 11). The values of EE and EC of the V2 alternative are comparable with those of V1. The results of the analysis confirmed the initial expectation that the optimised HPC frame structure is the most environmentally friendly alternative of the three assessed alternatives. The assessed high levels of mechanical and environmental performance of new silicate composites form a basis for the wider application of HPC in building construction in the future.

5.3 CS3: family house with hybrid timber and concrete structures

5.3.1 CS3: case study description

The subject of this case study was a single-family house located in Prague, Czech Republic (Hájek *et al.*, 2010). The three-storey house with ground plan dimensions of 9 m × 13·5 m is built on

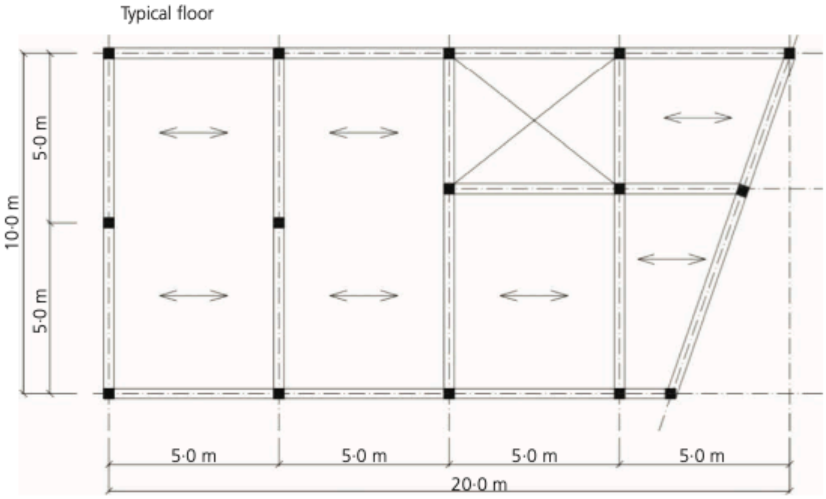

Figure 8. Ground plan of a typical floor of the subject of CS2 – a six-storey residential or office building

sloping terrain, so its basement with a garage is partially underground (see Figure 12). The business-as-usual practice of building such a family house according to current energy-efficiency standards is to use masonry walls (hollow ceramic brick blocks 440 mm thick) for the vertical structures and RC floor structures with hollow ceramic fillers. This business-as-usual design was the reference scenario (V0). However, the investor had a requirement that the house should be energy efficient and that the environmental impact should be minimised over the whole life cycle, so variant V1 was designed as a passive house built from business-as-usual materials (ceramic hollow brick blocks 240 mm thick with 300 mm external thermal insulation composite system (Etics) made of polystyrene, and RC floor structures with ceramic hollow fillers). The energy system consists of wood pellet heating, a solar thermal system and thermal water storage of 0·5 m^3. The mechanical ventilation unit is equipped with efficient heat recovery (efficiency ~80%). A photovoltaic system is placed on the southern part of the pitched roof with an installed peak power rating of 5·77 kW peak.

The design of V1 was further improved with the help of design strategies 1.D (the use of lightweight constructions) and 2.B (the substitution of conventional materials with bio-based materials), resulting in V2 described in the next section.

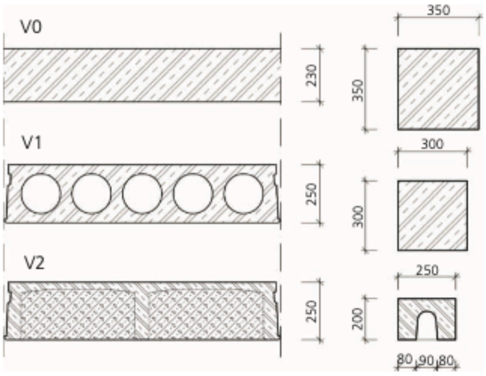

Figure 9. Designed structures in the variants of CS2. Left: typical vertical cross-sections of floor structures. Right: typical horizontal cross-sections of columns (dimensions in mm)

Figure 10. Samples of wood shavings concrete, which was used a floor structure filler in CS2

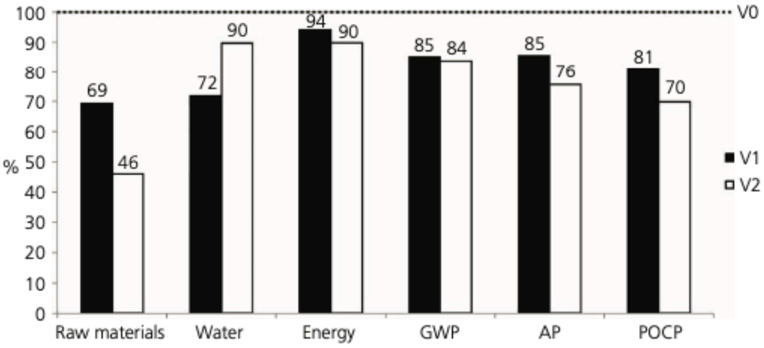

Figure 11. Aggregated results of CS2: consumption of raw materials, consumption of water, primary energy input, GWP, AP and POCP. A value of 100% represents V0 (reference level). Data from Hájek *et al.* (2014)

5.3.2 CS3: application of design strategies and resulting design

The application of the design strategies was limited by the fact that two sides of the first floor contacted the subsurface, so this floor used monolithic RC to resist soil pressures and to be waterproof. A far greater degree of design freedom was allowed for the rest of the building, whereby the strategy of flexible and adaptable design resulted in the decision to construct the weight-bearing vertical structures on the ground floor from concrete columns (V2). In V3, substituting the material of perimeter walls (business-as-usual hollow bricks) with timber structures (a two-by-four system) led to an additional lightening of the whole structure so that the dimensions of the load-bearing concrete columns of the ground floor could be minimised and hidden in the timber building envelope (Figures 13 and 14). The thermal insulation of the external walls has a *U* value of 0·11 W/(m^2 K), a result of massive thermal insulation composed of rock wool. The mean value of thermal transmittance of the building envelope does not exceed 0·16 W/(m^2 K). In V1 and V2, the roof was retained as a timber structure as in V0, although more thermal insulation was added to achieve a reduction in operational energy. In V3, masonry internal partitions were replaced by structures with a timber structure filled with acoustic insulation and covered by plasterboards.

5.3.3 CS3: assessment methodology

Detailed calculations of environmental impacts and resource use were calculated for the ground floor of the finished house, which was a functional unit (including load-bearing structures, partitions and external walls with thermal insulation). Besides V0 (the business-as-usual reference variant), V1 was assessed as a house of the same shape and purpose, built in a typical fashion for passive house standards (ceramic hollow brick blocks 240 mm thick with 300 mm Etics made of polystyrene and RC floor structures with

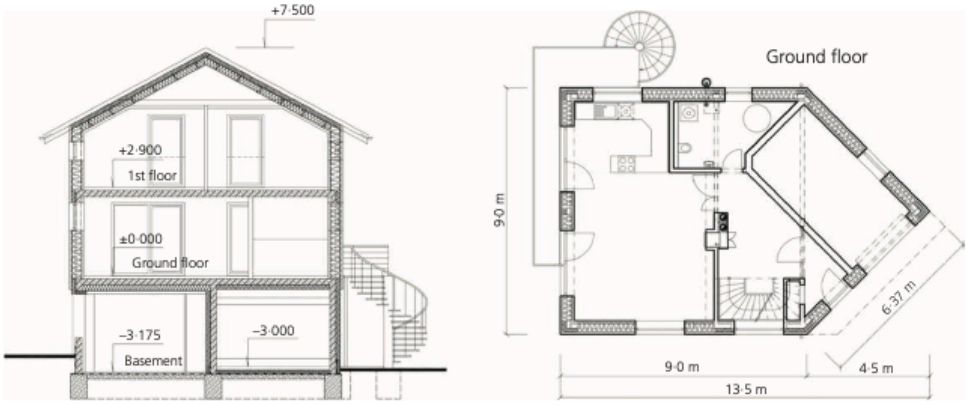

Figure 12. A family house (CS3). Left: cross-section. Right: plan of ground floor. Source: investor's documentation for building permit

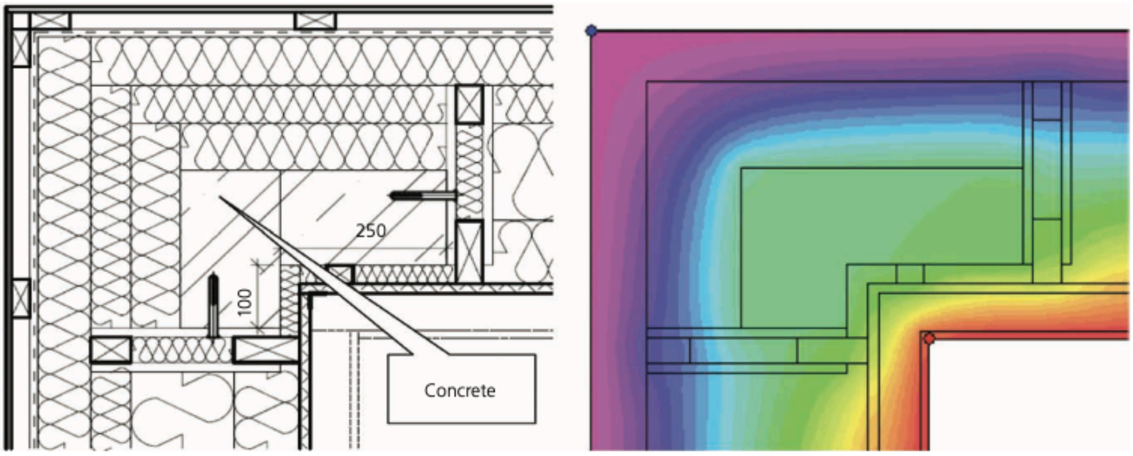

Figure 13. Minimised concrete columns are hidden in the building envelope (CS3). Left: detailed horizontal cross-section of the building's ground floor corner. Right: simulation of temperature distribution for winter design temperatures (to check that there is no risk of humidity condensation on the concrete structure). Source: Tywoniak and Staněk (2011)

Figure 14. Construction of the family house from CS3. Left: structure of the second floor and timber frames of the third floor. Centre: complete structural system, prepared for installing a sandwich of external walls; thermal insulation is placed inside. Right: the nearly completed house

ceramic hollow fillers), and V2 was assessed as a light RC frame structure with timber external walls and timber internal partitions. The LCA was conducted as a simplified cradle-to-gate cycle. The reference flow was defined as the materials needed for the creation of a functional unit. The environmental data were taken from the *Passivhaus-Bauteilkatalog* (Waltjen, 2008).

5.3.4 CS3: results

The results (Table 3, Figure 15) show that the optimised structure V2 has lower EE and EC compared with passive house V1 built in typical fashion (hollow brick blocks and Etics) and also compared with V0 designed for the basic acceptable energy standard. Moreover, the thickness of the designed external walls in V2 was reduced to 410 mm compared with 470 mm in V0 and 560 mm in V1. It is important to note that the functional unit did not take into account thermal properties; thus, the significantly improved U values for V2 are a bonus additional to the mostly lowered environmental impacts. The only indicator that increased in V2 compared with V0 was acidification potential. The increase in embodied sulfur dioxide equivalent emissions was derived from RC used for columns and from mineral wool used as thermal insulation in V2.

6. Discussion

6.1 Overall results

The overall results of the three case studies are summarised in Table 4. The achieved reductions in EE were 10% in CS2 and CS3 and 59% in CS1. Reductions in EC were 93% in CS1, 16% in CS2 and 32% in CS3. It is important to note that the boundary conditions of the observed case studies varied as well as the data sources for environmental data.

6.2 Variability in the effects of design strategy implementation

The case studies show that the reductions in EE and EC resulting from improvements achieved through design variants and the optimisation of buildings and their elements can vary from minor

	Standard solution (V0)	Standard passive house (V1)	Hybrid solution in passive standard (V2)
Weight of materials: t	66·8	51·9	59·9
Embodied primary energy input (non-renewable): GJ	146·0	158·4	130·8
Embodied carbon dioxide equivalent: t	10·9	9·9	7·5
Embodied sulfur dioxide equivalent: kg	35·5	37·8	42·9
U value of external wall: W/(m^2 K)	0·30	0·12	0·12
Thickness of external wall: mm	470	560	410

Source: Hájek *et al.* (2010)

Table 3. Comparison of three variants of the hybrid concrete–timber ground floor of the assessed house

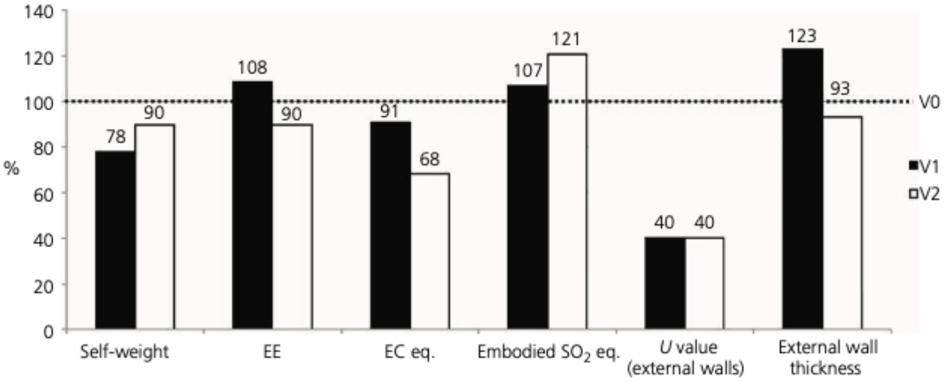

Figure 15. Comparison of environmental impacts and technical properties of three design variants of the ground floor (CS3): standard masonry structure (reference level, V0), masonry structure in passive house standard (V1) and hybrid concrete–timber alternative (V2)

(10% of EE in CS2 and CS3) to very significant (93% reduction of the carbon dioxide footprint of the CWS panel in CS1). The lessons learned also include the realisation that improvements in some indicators may be accompanied by a worsening in others (e.g. CS3-V2 – reduced EE and EC but increased acidification potential).

6.3 Comparison of results with other studies

CS1 describes the prefabricated facade element developed for retrofitting existing buildings with a skeleton load-bearing system. In this case, the significant reduction of embodied impacts (compared with the business-as-usual scenario) is related to the fact that most of the materials used were renewable materials. In another project, smartTes focused on the design of a universal prefabricated modular facade retrofitting system, for which the embodied environmental impact was calculated (Le Roux and Ott, 2014). These authors compared the Tes EnergyFacade system, which is composed of natural materials as far as possible, with standard Etics, and claimed a significant reduction in embodied environmental impacts.

CS2 illustrated a reduction in embodied environmental impacts by the lightening of structures and the utilisation of innovative materials (UHPC), which allowed the key properties of the building structure to be retained along with reduced dimensions of structural elements. A similar design principle was studied by Hájek *et al.* (2012), who proposed the use of UHPC for wood–concrete composite floors. A wood–concrete composite with a wooden beam and a concrete slab can be used instead of a conventional wooden beamed floor where better fire resistance, acoustic parameters or horizontal rigidity are required. The use of a UHPC slab without standard reinforcement reduces the thickness of the slab and leads to lower embodied GHG emissions and EE (compared with those of a composite with reinforced slab). In addition, case studies 1 and 2 reported in IEA EBC Annex 57 (IEA, 2016c) show that the replacement of a heavy structure with a lighter alternative (a RC skeleton replaced by a timber skeleton) also leads to a reduction in building foundation elements. In CS2 of the present study, the impact of reduced foundations was not studied, but such foundations would have been likely to generate further reductions in embodied emissions.

	Subject	Design stage	Applied design strategies	Max. achieved savings in EE: %	Max. achieved savings in EC: %
CS1	Curtain wall facade elements using bio-based materials	Building elements	■ Substitution for bio-based materials ■ Use of innovative materials with lower environmental impacts ■ Reduction of construction stage impact ■ Design for low impact of end-of-life stage	59	97
CS2	Lightweight structural system based on advanced silicate materials and recycled materials	Structural system	■ Lightweight constructions ■ Utilisation of recycled materials ■ Use of innovative materials with lower environmental impacts	10	16
CS3	Family house with hybrid timber and concrete structures	Whole building	■ Flexible and adaptable design ■ Lightweight constructions ■ Substitution for bio-based materials	10	32

Table 4. Overview of presented case studies and achieved savings in EE and EC

CS3 reveals that the meaningful utilisation of timber structures as replacements for ceramic or concrete blocks can lead to a significant reduction in EC and EE. Other case studies analysed under Annex 57 have arrived at similar conclusions. For example, Malmqvist *et al.* (2011) compared the embodied impacts of a RC frame to a timber structure in a study of a four-storey residential building. Their results showed that the timber-based variant brought about a 20% reduction in embodied GHGs. Wallhagen *et al.* (2011) analysed the embodied GHG emissions of an office building by comparing various alternatives and claimed a reduction in embodied impacts of 30%. In short, several case studies have now confirmed that the basic principles of the design strategies used here do indeed work. However, the methodologies and data sources of the existing case studies vary, which means that some caution should be applied when comparing results between studies.

6.4 EE and embodied GHGs against other environmental indicators

As shown in the results of CS3 (Figure 15), a design leading to reductions in EE and EC does not necessarily mean improvement in the entire array of important environmental indicators. In the case of CS3, the design that reduced EE and EC led to a 21% increase in embodied AP compared with V0 (which could be offset by a significantly lower energy consumption during the building's operation) and also led to a 13% increase compared with V1 (with a similar designed operational energy efficiency).

7. Conclusions

7.1 The introduction of design strategies

Various design methods for reducing the levels of EE and EC are used by architects and engineers, either intentionally or by intuition. The work presented here has introduced the design strategies drafted in Annex 57 and applied them in three case studies of design optimisation for building elements, for a building structural system and for a part of a whole building. In all three cases, the proposed designed strategies achieved improved environmental performances in most of the chosen indicators. The work group of ST4 in Annex 57 is working on identifying and describing these strategies with respect to real examples so that they can become taught and used intentionally and in a systemic way. The education role will be supported by an extensive categorised set of case studies from various countries, so that a user can easily find a case study related to his or her project and become inspired, knowing what the effect of a particular measure could likely be.

7.2 Application of the proposed design strategies

The case studies presented in this paper show that the procedure of applying the proposed design strategies is correct and beneficial for improving the environmental indicators of construction solutions. CS1 clearly showed that a sophisticated substitution of conventional materials can lead to substantial reductions in several environmental impacts and to a completely new and multi-purpose construction solution. CS2 presented the combined environmental benefits of lightening a structural system by using innovative materials and recycled, rather than raw, materials. CS3 illustrated the potential reduction in EC and embodied non-renewable primary energy in the construction of a typical floor of a family house using the strategy of lightening the structures and substituting silicate materials with bio-based materials.

7.3 Construction innovations and the need for a holistic approach

From the construction point of view, some of the approaches typically recommended to be avoided, such as the mixing of various construction technologies in one building (the timber–concrete hybrid in CS3), can lead to environmental benefits. As shown in CS2 and CS3, it is not sufficient to assess a material or building element on its own – the context of the whole building is needed. Materials that have higher environmental impacts per unit of mass can be utilised in a way that reduces the environmental impacts of a whole building; for example in CS2, the UHPC has higher EE and EC per cubic metre of concrete (compared with commonly used types of concrete), but its use allows more structural elements to have reduced dimensions, resulting in overall fewer cubic metres of material used. It is always necessary to take into account the material, element and whole-building levels when undertaking optimisations.

7.4 The need to consider more environmental indicators

The finding that a reduction in EE and EC is in some cases accompanied by an increase in other environmental impact indicators needs to be further investigated in more case studies comprising a wider spectrum of indicators. Overall priorities and targets in the protection of the environment must be taken into account by policymakers, who, in many cases, tend to stress only the need for reducing energy consumption and transitioning to a low-carbon dioxide economy, neglecting some possible side effects.

Acknowledgements

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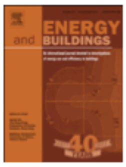

Application of building design strategies to create an environmentally friendly building envelope for nearly zero-energy buildings in the central European climate

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ABSTRACT

The paper contributes to the fulfilment of the environmental targets of the EU by introducing an innovative solution for envelopes of nearly zero-energy buildings (nZEB). It presents the development of an environmentally friendly alternative to aluminium curtain wall systems for new constructions or renovations.

The research and development were from the early stages led by design strategies for low embodied energy and embodied carbon structures. The first technical concept was analysed using comparative life cycle assessment (LCA). Prototypes were tested to verify their technical performance (air- and water tightness, fire resistance, acoustic properties, short- and long-term hygrothermal monitoring). The final pre-production design was subjected to a detailed LCA, and various possibilities for its improvement were suggested and assessed.

The early-stage LCA showed a high potential for reduction of the embodied environmental impact by utilization of natural materials. The results of the experimental testing proved that thus developed curtain wall system fulfilled the standard technical requirements. The detailed pre-production LCA study proved that the fabrication of one panel of the curtain wall system being developed causes significantly lower environmental impact compared with a panel of a common aluminium curtain wall system.

1. Introduction

The present paper contributes to the achievement of the overall climate- and energy-related targets of the European Union and other world authorities by the introduction of an innovative solution for nearly zero-energy buildings. It presents an approach to designing an environmentally friendly alternative to aluminium curtain wall systems for new construction or renovation of public buildings, including its experimental verification.

1.1. Scope and background

According to Europe's buildings under the microscope [1], 25% of the European building stock is represented by non-residential buildings and 48% of existing buildings were built between 1961 and 1990. Research and development presented in this paper are focused mainly on non-residential buildings featuring light panel curtain walls (CW) built in former Czechoslovakia between 1961 and 1990, which are now after 30–55 years of operation due for retrofitting.

The estimation is that every tenth non-residential building built in the time period has such a type of envelope, so the results are generally applicable to, at least, 1.2% of building stock in Czechia [2] with a very similar situation in Slovakia. The authors do not have exact numbers on hand; however, it is a known fact that buildings with similar façades can be found not only in many cities of the former communist bloc (Fig. 1) but even outside Europe. These buildings have a load bearing superstructure—typically made of reinforced concrete or steel—and were usually used for such types of buildings as schools, kindergartens, office buildings, medical centres, fire and police stations, railway facilities, hotels, and restaurants. Their typical issues related to light building envelopes are (see Fig. 2): faded colours, obsolete look and loss of attractiveness, insufficient level of thermal insulation, malfunction of window hinges and locks, failures of fixing and seal elements, wa-

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Abbreviations: AP, Acidification Potential; CW, Curtain Wall; EP, Eutrophication Potential; EPD, Environmental Product Declaration; EPDM, Ethylene Propylene Diene Monomer; GHG, Green House Gas; GWP, Global Warming Potential; HVAC, Heating, Ventilation and Air Conditioning; LCA, Life Cycle Assessment; nZEB, Nearly Zero-Energy Building; PEI_{nre}, Non-renewable Primary Energy; PVC, Polyvinyl chloride.

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Fig. 1. Aluminium-based curtain walls examples (Pilsen, Prague, and Leipzig).

Fig. 2. Details of aluminium and glass curtain wall on building from 1970s on various buildings in Pilsen, Czechia.

ter leakages, insufficient airtightness resulting in winter discomfort and high operational cost.

These buildings also lack shading devices, which cause summer overheating. Moreover, some of the elements may contain asbestos boards hazardous to health. In addition to the issues assigned to the envelopes, these buildings also suffer in building services with the related low levels of user comfort: obsolete heating systems with poor control, outdated electric installations and water piping, malfunctioning or often non-existent heating, ventilation and air-conditioning (HVAC) systems, and ad-hoc basis data infrastructures [2].

Many of these buildings in Czechia have been successfully retrofitted in the past 15 years, but a significant portion of the building stock still waits to be retrofitted. When planning to retrofit existing building with curtain walls, the following technical scenarios are usually considered: a) complete replacement of the existing curtain wall with a new one; b) partial replacement: principal frame remains, new structural elements are added together with the filling, cladding and windows; c) complete replacement by a light masonry wall (usually made of aerated concrete) with an external thermal insulation composite system and new windows. The choice of technology is determined by the overall architectural design, total size of the building, and available budget. [3]

One of the typical solutions possible for the obsolete curtain walls on existing buildings is to replace the existing panels with new ones. The new panels are usually made from a structural metallic frame with glazed or metallic external surface finishing. Compared to the original panels, the new ones usually have a significantly improved U-values enabling a substantial reduction of the operational energy demand of the whole building. An experience from one of such typical renovation processes (that took place literally in the offices of the authors) led to a discussion on the ratio between embodied and operational energy of near-zero energy buildings (n-ZEBs) and consequentially to the research question whether it is possible to have a modern curtain wall with key features similar to the typical metallic curtain walls but with a significantly reduced need for energy used for their fabrication. Hence a project on this topic was initiated, and once financing was in place, research and development works started.

1.2. Objectives

The main objective of the research was to apply design strategies for low embodied energy and embodied carbon to a design of a new panel curtain wall (CW) system applicable in central Europe in such a way that the CW system would: i) be suitable for the creation of envelopes of new buildings or as a replacement for obsolete curtain walls of existing buildings; ii) enable the building, to which the system is applied, to reach the nearly zero-energy standards; iii) need less primary energy and cause lower amounts of carbon emissions during its production stage compared to standard metallic curtain walling systems, whilst matching or surpassing these systems in physical and functional properties.

The main objectives of the present paper are to outline the design approach performed in Czechia, present how the technical challenges were tackled, how the technical properties of the final prototypes were tested and show how the life cycle assessment applied during the project stages to meet the requirements of achieving relatively low embodied primary energy and carbon footprint of the final design.

The target audience of the paper is practitioners in green building—architects, designers, consultants, producers of building products and construction companies—and researchers in lifecycle assessment and energy and environmental impact of buildings.

2. Methods and assumptions

During the development, the team has been looking at the original curtain walls and their properties and thought about possible improvements. The environmental impact of the original curtain walls was determined by the three features: the operational impact (resulting from energy demand for heating and cooling), the embodied impact of the construction elements, and the overall durability of the curtain wall.

In the first stage of the design process of a new CW, the following design targets were set:

a) the environmental impact of the building operation (described by primary non-renewable energy consumption and acidification, global warming and eutrophication potentials) to be reduced by replacing the original curtain wall by a new one with increased thermal resistance;
b) a significant reduction of the embodied emissions and primary energy to be reached by application of a new design (compared to contemporary metallic CWs available on the market);
c) the solution to be equally durable to the usual systems on the market so that the projected lifetime of the CW will be similar as for the standard solutions.

2.1. Reduction of the operational impacts

The operational energy consumption of a building is directly related to the thermal parameters of its building envelope. The operational thermal performance of a CW can generally be determined by setting its thermal transmittance. At the time of the construction of the building types in question—with metallic CW—new legal requirements for the thermal protection of buildings started to be applied in the country (1962). Thus, the entirely insufficient values of thermal parameters of the structures from today's perspective were used: for the metallic CWs, the values of the heat transfer coefficient of approximately $1.5\,W/m^2{\cdot}K$ and of $3.7\,W/m^2{\cdot}K$ for the window fills. Regarding the many sizes and shapes of buildings suitable for the CW application, a set of parametric calculations were carried out to determine the average energy performance of these buildings and their potential for improvement [4,5].

For a parametric study, the Building Optimizer program was used. It compares a set of 1000 fictitious objects with any combination of input parameters between the two entered boundaries. The input parameter limits (size, geometry, number of floors, and percentage of glazing) were selected according to the typical objects on which metallic CWs were used at the time of their construction.

The average specific heating demand of $810\,MJ/(m^2{\cdot}year)$ of floor area was calculated for a given set of typical objects with the original CW. Obviously, this original state allows achieving significant savings. At the same time, the renovation of a façade always fundamentally affects the behaviour of the internal environment, in both winter and summer periods. The aim of the development of the new CW was to go beyond basic legal requirements and to get closer to the values recommended for passive house standards [6]. Such approach can be assumed as a valid method for major savings in operational energy demand and operational environmental impact [7,8].

2.2. Reduction of embodied impacts

The building design strategies for reduction of the embodied primary energy and embodied emissions of greenhouse gases (hereafter referred to as PEI&GHG) were introduced by Annex 57 ("Evaluation of Embodied Energy and Carbon Dioxide Emissions for Building Construction") within the framework of Energy in Buildings and Communities under the International Energy Agency [9,10]. The design strategy has four main elements [11]: 1) reducing the overall consumption of materials throughout the entire life cycle; 2) substituting conventional materials with alternatives that have lower environmental impacts; 3) reducing the impact of the construction stage; and 4) designing for a low-impact end-of-life stage. Each of the four areas is further divided into more concrete measures (see Table 1).

2.3. Design process

The design works started with research on the existing curtain wall systems available on the market including a list of the key requirements, description of typical materials applied and assembly and installation procedures. These inputs were deeply analysed, and these design strategies were identified as favourable both by the authors and the literature [12–15].

The first two design strategies were applied by taking the design of a typical aluminium and glass panel as a reference design, while we tried to replace as much materials as possible by simple bio-based alternatives. In the cases where simple material did not match technical requirements, we were looking for new materials, preferably bio-based with low environmental impact.

With the focus on one building element design (building envelope), it was only possible to consider the material shell assessment.

Attention was also paid to the impact of the use phase and disassembly at the end-of-life phase. The materials were carefully selected to provide sufficient reliability during the CW's lifetime so that the impact of the use phase should not be higher than for the usual CW. The use of prefabricated panels made of natural material and bound together mainly by mechanical elements enables simple disassembly at the end of the elements' service life and relatively easy separation of the used materials for further reuse or incineration. Glass from windows can be easily recycled as well as the steel anchoring material. A problem could be anticipated with the seals; therefore, the ethylene propylene diene monomer (EPDM) rubber seals with an expected lifetime of 40 years minimum were chosen.

2.4. Compared variants

The research team worked with three major variants of CW in different typologies that are presented in this paper. These were:

1) The reference, contemporary aluminium-based CW:
    a) transparent with a window (A1)
    b) opaque (A2)
2) Early new CW with environmentally beneficial design (after one-step optimisation):
    a) transparent panel with a window (B1)
    b) opaque panel (B2)

Table 1
Overview of design strategies for reduction of embodied energy and embodied carbon emissions (according to [11]).

Design strategy	Measures
Reduction of the overall consumption of materials throughout the entire lifecycle	■ Reuse of existing building structures
	■ Optimisation of building form and layout plan
	■ Flexible and adaptable design
	■ Lightweight constructions
	■ Low-maintenance design
	■ Components' service life optimisation
Substitution of conventional materials with alternatives that have lower environmental impacts	■ Utilisation of recycled materials
	■ Substitution with bio-based and raw materials
	■ Use of innovative materials and technologies with lower environmental impacts
Reduction of construction stage impact	■ Preference of local materials
Designing for a low-impact end-of-life stage	■ Design for disassembly
	■ Use of materials that are recyclable using present recycling technologies

3) Further optimized new CW after a two-step environmental optimization:
   a) transparent with a window (C1)
   b) opaque (C2)

The reference case (A-variant) was built-up upon the usual aluminium-based CW available on the market. Specifically, the calculation was based on the exact documentation of the CW used during the refurbishment of the 14-storey building of the Czech Technical University in Prague [16].

Moreover, a general, original building envelope was assumed for a calculation of the original building's energy consumption. Beside the compared design, there were additional measures applied to the newly-designed B-variant to improve the acoustic or fire properties. All the variants are closely described further below.

3. Technical concept development and evaluation

The application of the design strategies together with the requirement for the building operation impact decreases in the specific case of the curtain wall design created the need to reconsider the particular materials used for each element of the curtain wall. Research has been already done towards a sustainable development of curtain walls: Azarai and Kim [17] studied in particular the change of the materials of CW's mullions and emphasized the need for a life-cycle approach to its design and in another study Densley Tingley et al. [18] examined various thermal insulating materials in the building envelope from the LCA perspective. Citherlet et al. [19] assessed the impact of advanced glazing units. These research works showed the particular steps needed to reach the innovative, environmentally friendly design.

Despite the clear principles, the technical qualities of substituent materials avoided the straight-forward solutions. For instance, it was not possible to use standard timber beams for the load-bearing frame due to the requirements for dimensional stability of the elements and strict machining tolerances—so it was decided to opt for laminated veneer lumber. In another case, a hard (bearing) piece of thermal insulation was needed, and a wood fibre thermal insulation or a wood fibreboard would be too unstable for such purpose—so a cork bar was used instead. In cases where a reduction of the need for maintenance or future surface treatment (such as regular painting) was required, thermally treated wood elements were used (Thermowood in this case). The described efforts resulted in the design of the main structural frame of laminated veneer lumber (instead of aluminium); wooden window frames with external cladding from thermally treated wood (instead of aluminium); and a thermal insulation layer made of wood fibre and cork (instead of glass wool and polystyrene).

3.1. Technical challenges: fire and acoustic qualities

The replacement of well-known and tested materials in the CW construction brought various reservations against the new design. The key technical qualities had, therefore, to be tested before the CW could enter the market.

One of the major concerns the investors can have when considering the more environment-friendly alternative represented by the wood-based CW application would probably be the fire risk due to its combustibility. To allow its wider use, the risk had to be assessed in two ways: firstly, to limit the possible fire spread on the façade to another fire compartment and, secondly, to prevent the possible fire spread to another building.

The first problem relates mainly to the use of combustible materials on a façade (combustible cladding); however, in several cases it is also necessary to consider the materials inside the façade structure. This problem is encountered mainly in higher buildings or buildings with specific functions, such as warehouses, assembly halls or hospitals. The fire intervention there is more complicated and takes more time, and spreading of the fire in these places must be eliminated under all circumstances. In some cases, sufficient solution is represented by a fire barrier (an incombustible stripe of façade) installed on the fire compartment boundary. In Czechia, combustible CW can be used for a large percentage of non-residential buildings' facades up to 4 or 5 storeys. In other cases (e.g. hospitals and theatres), the use of the combustible façade is forbidden.

The problem of possible fire spread to adjacent buildings seems to be more critical because it affects all buildings with a timber façade. In the case of fire, protection of the area surrounding the subjective building should be provided and, therefore, sufficient separation of distances, where there is an imminent risk of the spread of fire, must be determined. In this area, any other fire compartment or any other neighbouring building cannot be located. Among many possibilities of fire spread, such as flying brands, burning debris direct flame contact or convective heat transfer of hot gases, the radiative heat transfer is considered to be the main risk. Considering this criterion, calculation of a sufficient separation distance according to Carlsson [20] is bounded with a line of critical radiative heat flux varying from 12.5 for piloted ignition to 30.0 $\mathrm{kW/m^2}$ for self-ignition and the value of separation distance depends mainly on the sum of unprotected areas on the fire compartment façade.

An unprotected area is any part of the CW that can contribute to radiation during a fire: parts without fire resistance (e.g. door, window or any other structure without proven fire resistance) or parts that emit radiant energy, such as structures with a combustible cladding, must also be taken into account [21]. Obviously, the bigger the unprotected area is, the larger the separation distances are. A wood-based CW without fire resistance covering a large fire compartment results in large separation distances, and it could either limit the building location on the plot (when new building with combustible curtain wall is designed) or even make retrofitting of existing buildings' CW impossible because it would affect the existing neighbouring buildings.

Building envelope plays an important role in providing a sufficient level of acoustic comfort to the users of the building. The dominant outdoor source of noise in urban areas is the road traffic. A CW shall reduce the noise transmission from outside to inside for achieving acceptable noise levels in rooms, given by regulations and standards. Reduction of the overall consumption of materials in environmentally friendly structures and the preference of natural materials leads to the lightening of the curtain wall system. Such elements have complex acoustic behaviour with great differences in sound insulation between low and high-frequency regions. This is caused by the multi-layer character of these CWs and, especially, the corresponding acoustic effect called mass-air-mass resonance. It is coming from a presence of the air cavity (filled with fibre thermal insulation) between the two plates. Regarding the reduction of sound transmission, poor sound insulation at low frequencies is unfavourable because the road traffic noise has significant low-frequency components. Therefore, so-called spectrum adaptation terms C and C_{tr} were introduced into the rating system given by ISO 717-1 [22] in the past. The C_{tr} parameter relates to the traffic noise, and when added to the apparent weighted sound reduction index of the facade, that is $R'_w + C_{tr}$, it represents the difference in A-weighted sound pressure levels, which better describes the actual airborne sound insulation. For this reason, the development of the new curtain wall system took the C_{tr} spectrum adaptation term into account, although in Czechia, like in some other European countries, regulations and standards simply require the use of the apparent weighted sound reduction index R'_w.

3.2. Environmental impact

The design strategy led us to an application of the different materials with more favourable environmental impacts compared to standard solutions; however, the above-mentioned technical requirements set certain limitations for the design. Therefore, the environmental effectiveness was evaluated twice. At first, it was the preliminary design assessment in the early design stages, and later it was the tested solution assessed more in detail. In both phases the life cycle assessment's (LCA) border conditions were set similarly in accordance with ČSN EN ISO 14040 [23].

The functional unit of one standard curtain wall's module was selected: 3.3 m high, 1.5 m wide with the window 1.8 m high and 1.4 m wide in the case of modules with a window (variants A1, B1, and C1). The total area of all modules was 4.95 m^2, similar for all modules. The general U-value of opaque parts was set at 0,16 W/(m^2·K) and the estimated lifetime was set at 40 years. The values are further stated for the functional unit, e.g. one module of CW.

Environmental impact was assessed using the set of selected mid-point indicators complying with ČSN EN 15804 [24] used for the environmental product declarations:

- GWP_{100a} [kg $CO_{2,equiv.}$] - Global Warming Potential
- AP [kg $SO_{2,equiv.}$] - Acidification Potential
- EP [kg $NO_{x-,equiv.}$] - Eutrophication Potential
- PEI_{nre} [MJ] - Non-renewable Primary Energy

For the operational impact values, the indicators will be stated in "/m^2.year" values related to the floor area of the model building. Materials advantageous in one indicator may be at the same time disadvantageous when evaluated according to another indicator. The selected set of indicators allowed describing the multi-criterion problem of the assessment of the curtain wall's impact on the environment.

The calculation was made within the cradle-to-gate system borders. The system contained the production of the raw materials, their processing, and transport to the gate of the factory.

At the preliminary stage of development, the lifecycle inventory was done using the early technical documentation once it was provided. Only the major elements of CW were included in the rough calculation (main bearing elements, thermal insulation, steel anchors and window frames and glazing and sealing). The selection was made from the constructional and technological perspective and mass of the elements. A more detailed assessment was not appropriate because the development was at an early stage when a lot of details still had to be settled. In order to verify the reasonability of the design approach, the environmental impacts of the early design were compared to their most frequent competitors: metallic curtain walls and silicate-based masonry walls with external thermal insulation.

Later, when the development came to the prototyping phase, the inventory was re-elaborated using the final production documentation of the CW. It became possible to incorporate more elements in detail and provide a more exact overview and comparison between the usual and developed curtain wall alternatives.

In both cases, the mass of materials used for the functional unit was collected and calculated in a spreadsheet. The lifecycle impact assessment data used in both phases differed: the Environmental Product Declaration data were selected for the early design assessment, whereas the Ecoinvent 3.3 [25,26] database was used for the detailed assessment within the "Allocation, cut-off by classification" system model. The Europe-localized data were used. The Ecoinvent data contains the burden from the primary production of materials whereas the recycled and secondary materials come burden-free (all the impacts are dedicated to the primary production). The only impact which these materials carry comes from the recycling and treatment processes.

For some materials, the exact datasets were not available, and thus calculations were made with the help of literature and manual modelling using Ecoinvents' processing data and other materials. This method was applied for thermally modified wood (modelling sawn wood production, wood preservatives production, polyvinylchloride production, nylon production, and raised energy consumption according to the producer [27] as the inputs), extruded aluminium elements (aluminium production and extrusion as the inputs) and wooden I-beams (sawn wood production and oriented strain board production as the inputs).

The sensitivity analysis was done to identify the possible modelling uncertainty impact on the overall calculation. The influence of changes in mass, GWP_{100a}, AP, EP, PEI_{nre} was tested for the modelled items. The influence on the overall results was minor —the GWP and PEI_{nre} unit parameters would have to be 4.7 times higher to equal the overall results of newly designed CW (B) to the original aluminium one. Thus, the modelling uncertainties were considered insignificant.

Even though the end-of-life stage was not included in the assessment, the durability tests were performed to prove the feasibility of the design. The substituent new CW should provide similar or higher quality to prove its competitiveness.

4. Results and discussion

4.1. Final design

All the prerequisites and legal and technical requirements were respected in the development of the final CW design. The general

Fig. 3. Assembly of main elements of curtain wall. The laminated veneer lumber frame in the left is fitted with steel anchors and covered with oriented strain board in the middle. The thermal insulation and window frame are mounted next followed by the module which is covered with a DHF board. The joints and other details are processed in the next step.

Fig. 4. Installation of curtain wall prototypes.

aim was the use of low impact natural materials. The main primary bearing structure was, therefore, made of laminated veneer lumber beams, which were processed using computer numerically controlled (CNC) machines. This solution offered sufficient dimensional stability of the frame in its details.(Fig. 3)

The bracing stability of the module was provided by oriented strain boards (OSB) from the interior and wood fibre board (DHF) from the exterior side (see Fig. 4). The OSBs are considered air- and vapour tight, so that the surface and joints specifically must be properly sealed. Contrary to that, the exterior DHF boards have very low water vapour resistance factor ($\mu \leq 11$) to ensure the vapour gradient in the required direction.

The space inside the frame was filled with wood fibre insulation with $\lambda = 0.038\,\mathrm{W/(m{\cdot}K)}$ in thickness of 240 mm. The critical details with reduced thermal insulation thickness (window blind area, window siding, etc.) are provided with cork insulation.

Vapour condensation and water penetration can be expected in the joints of the panels, so both vertical and horizontal joints are protected with aluminium laths. These also provide an exact placement for the synthetic EPDM rubber sealing profiles. The tightness of the module is, therefore, ensured by the application of the EPDM-bonded sealing and foils.

The exterior side can be finished with various surfaces – the ventilated façade is standard, but the material and surface treatment vary; standard options include wooden cladding, glass, cement fibre boards or framed or frameless photovoltaic panels. A compound facade can be used as well. The durability of the window siding was extended by use of thermally modified wood (Thermowood), which has increased resistance to moisture and mould growth compared to standard European wood types.

The overall thickness of panels about 250 mm is supplemented with a variable plasterboard wall, which accommodates all the ducts and wires of heating, ventilation or air-conditioning systems.

Several of curtain the wall's modules in various configurations were prototyped and tested (Fig. 4). During the tests, the changes in the design were suggested [28,29] so that the final design could be assumed to be competitive and dependable.

The following paragraphs illustrate the tasks that had to be solved in conjunction with the low embodied GHG and energy design of CW.

4.2. Thermal performance

With the focus on the desired decrease of operational energy and GHG emission, a lot of effort was put in the thermal qualities of the CW (thermal transmittance, mean thermal transmittance, thermal bridges, and energy performance of building and transport of water vapour through the structures). Several suitable opaque structures of the panel were proposed and evaluated. Thermal transmittance of the opaque part is in the range of $0.157\,\mathrm{W/(m^2{\cdot}K)}$–$0.079\,\mathrm{W/(m^2{\cdot}K)}$.

Lightweight curtain walls (CW) in general contain a large number of structural details which constitute thermal bridges. In a conventional CW (variant A below), heat energy flowing through

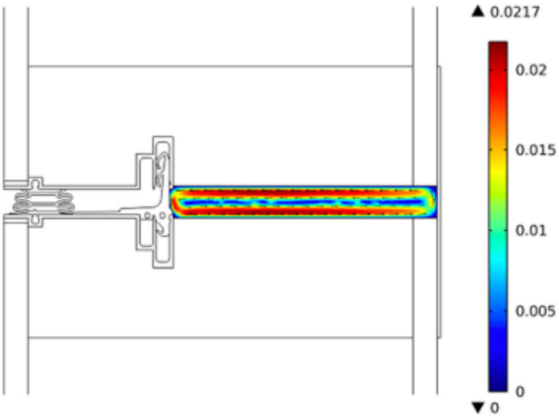


Fig. 5. Representation of calculated air flow speed (m/s) in the air cavity in horizontal joint.

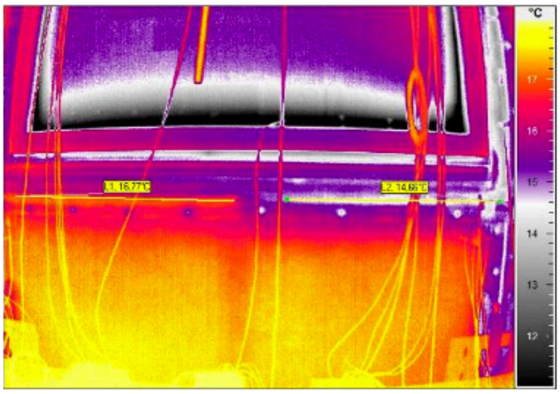


Fig. 6. Horizontal joint under the window in climatic chamber with a 36 °C temperature difference: left is filled with insulation and right is without insulation.

these details constitutes a significant part of the total heat loss because they are composed largely of aluminium. The designed wood-based CW (variants B and C) took a system of EPDM seals between the panels and an aluminium profile for mounting of the seals over from the aluminium CW. When they were used, the thermal bridges represented 38% of the total heat flow at a full panel of normal size (3.3 × 1.5 m). Using the aluminium profile also caused a risk of condensation on its inner surface. The large temperature differences in the air cavity supported air flow, as shown by calculations (Fig. 5) and measurements (Fig. 6). The aim of the following calculations was to verify the effect of replacing the aluminium profile with another less energy intensive and less thermally conductive material—plastic.

Average thermal transmittance (counting linear and point thermal bridges) of this solution achieves values of 0.51 W/(m^2·K) for the panel with 57% of glazing and of 0.25 W/(m^2·K) for the full panel. The glazed panel thus also meets the recommended value of heat transfer coefficient for passive houses for CWs 0.63 W/(m^2·K) ČSN 730540-2 [30]. It is possible to quantify the additional heat flux through all the thermal weakenings of a characteristic part of the CW using aluminium strips by the value of 0.10 W/(m^2·K).

Variants of joint details between panels considering plastic profiles for storing of EPDM seals were assessed next. Variants with interposition of thermal insulation into the air cavity for reducing the air convection followed. Temperature distribution in details is more uniform when using the plastic profile than with the aluminium one. Temperatures on the interior side of the profile increase up to 9 °C which can greatly reduce possible condensation in this location. These adjustments may reduce the heat flux through the detail up to 56%. It is possible to decrease additional heat flux through all the details of a characteristic part of the CW, and it is possible to decrease it with the plastic profiles to a value of 0.06 W/(m2·K). This change is also favourable from the point of the embodied environmental parameters of the CW.

After replacing the original CW for the designed wooden CW value, an average heating demand of 147.6 MJ/(m^2·year) was achieved, compared to the original 810 MJ/(m^2·year) for a typical building with the original metallic CW (82% reduction). The differences in the operational environmental impact between the original heating system (brown coal boiler) and typical contemporary Czech heating system (gas boiler) for both, original and new CW are presented in Fig. 7. The country-specific conversion and emission factors were used according to Vonka et al. [31] with the combined efficiency of the boiler and heating systems (57% and 93%).

4.3. Fire safety

In the field of fire safety, the least favourable behaviour of a CW needs to be assumed unless other behaviour (for example sufficient fire resistance) is proven. During the development, the improvement of the design had to be made to broaden the use variety of the new CW. A fire-resistant and fire non-spreading alternative was designed and examined. The main objective was to use as many identical elements as possible and to enable a combination with the regular panels. Hence the only crucial difference is the incombustible (gypsum-fibre, cement-fibre or vermiculite) board covering around the same combustible core as for standard panels. In the exterior, only an incombustible façade board or external thermal insulation composite system could be mounted.

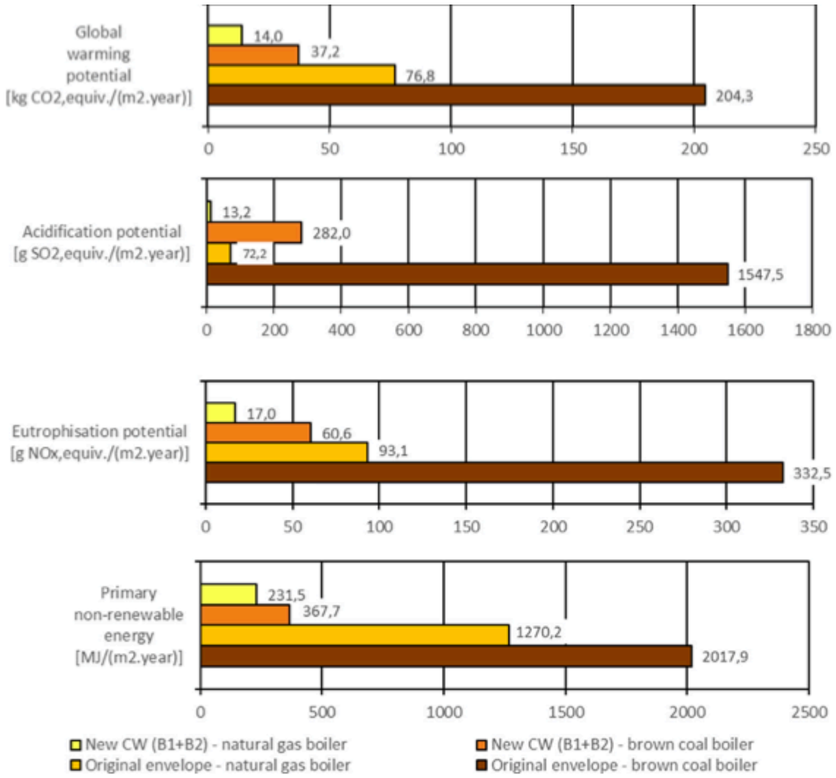
The fire-resistant panel was tested in a furnace both from the exterior and interior, and according to European standards [32], it reached fire resistance $EI_{o \to i}$ 90 from outside and $EI_{i \to o}$ 60 from inside, respectively. It was also proven that there was no fire spread on the facade.

4.4. Acoustic qualities

Most curtain wall systems consist of large panels that are fastened to the load-bearing structure of a building. The airborne sound reduction index of each panel mainly depends on its dimensions, the thickness of the air cavity (and its filling ratio), the surface mass of boards, the distance and the type of sound bridges (typically the wooden supporting frame around the panel edges), and many others. From the point of acoustics, the new CW panel has the following composition: OSB board (9 $kg.m^{-2}$) on the interior side, air cavity (240 mm) filled with wood fibre insulation, and vapour-permeable dense wood fibreboard (approx. 9 $kg.m^{-2}$) on the exterior side.

The sound insulation of the resulting façade system is also beneficially influenced by the properties of expansion joints between the panels. In a standard variant, they are sealed with two-stage rubber gaskets inserted between the panels during installation. The designed curtain wall was tested for airborne sound insulation according to ČSN EN ISO 10140-2 [33] and ČSN EN ISO 10140-4 [34] in the acoustic laboratory of the University Centre for Energy Efficient Buildings, Czech Technical University in Prague (Fig. 8).

The measured weighted sound reduction index of a standard wall is 41 (−2; −6) dB. Compared to the current Czech requirements, this value is high enough for the façade to be used in almost all areas where the limits of traffic noise levels are not ex-



. 7. Comparison of the operational environmental impact indicators for original building envelope and new CW in the building with original brown coal (combined iciency 57%) and contemporary natural gas (combined efficiency 93%) heating system.

Fig. 8. Installation of the curtain wall system into the test opening in the laboratory (left), test specimen with applied cardboard/sand boards (right).

eded. However, there are two frequency regions with relatively w sound insulation (around 100 Hz and 2500 Hz). Also, the spec- ım adaptation term is a large negative number, which gives the lue of $R_w + C_{tr}$ equal to only 35 dB. To improve the sound insu- :ion, one layer of insulation board consisting of cardboard and nd was added to the interior side of the panels. Repeated acous- : tests showed an increase in the weighted sound reduction in- x R_w of 9 dB (from 41 dB to 50 dB) and, what is more, of 11 dB $R_w + C_{tr}$. The last result is the same as for standard panels with dependent plasterboard wall lining, which were also tested for und insulation.

4.5. Life cycle assessment

The results of preliminary assessment showed significant potential to complete the development successfully. The preliminary calculation showed the design was well on its way to reaching the goals: the first results showed the possible reduction to one-third of the embodied non-renewable primary energy in comparison between the new design (B, C) and the original metallic one (A). The masonry with external thermal insulation showed similar results in embodied energy. Those results were published and presented separately [2,3].

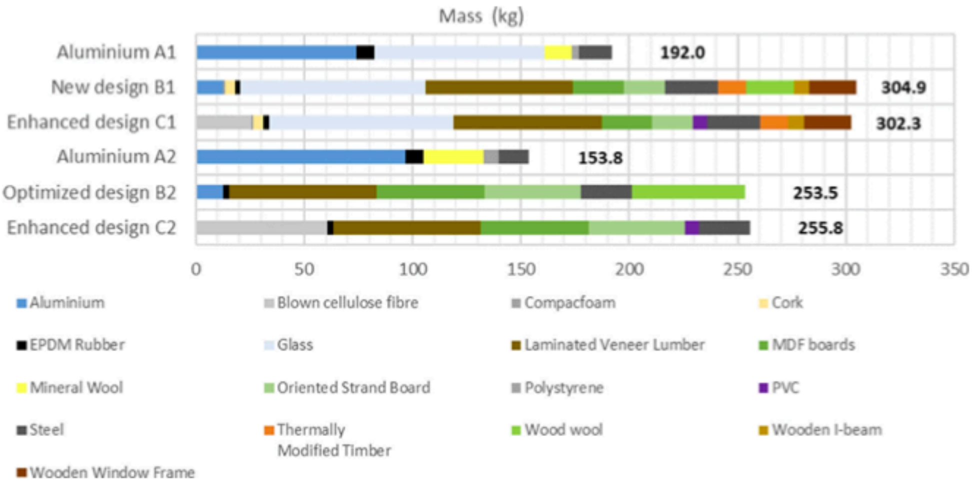


Fig. 9. Mass distribution between materials in curtain walls' alternatives - a panel with a window A1-C1, opaque panel A2-C2, all with a similar area of 4.95 m^2.

Table 2
Overall results of the assessment.

Indicator / Variant	A1	A2	B1	B2	C1	C2
GWP_{100a} [kg $CO_{2,eq.}$]	942.2	1033.5	484.4	290.6	393.5	214.9
AP [kg$SO_{2,eq.}$]	5.73	6.04	3.08	1.68	2.53	1.25
EP [kg $(PO_4)^{3-}$ $_{eq.}$]	2.46	2.40	1.86	1.12	1.68	1.02
PEI_{nre} [MJ]	13 876	15 519	6514	3764	5459	2923

As soon as the technical quality tests were made and the technically optimized solution was set, the bill of materials could be provided. The bill of materials for the aluminium curtain wall (CW) was calculated based on the real construction documentation of the contemporary aluminium curtain wall delivered for the refurbishment of Czech Technical University's building [16].

The mass distribution of materials is presented in Fig. 9. The aluminium CW had the lowest total mass per functional unit: 192 kg (A1) and 153.8 kg (A2) whereas the new CW (early design) had 304.9 kg (B1) and 253.5 kg (B2) per unit. In A1 and B1 cases, the main contributor was the window frame and the triple glazing (41% and 28% of the total mass of the unit). This seemed rather unfavourable for the new design—it might bring additional impact caused by the transportation and montage phase (elevating the units, etc.). The main reason was, in particular, the lower strength of the wood-based materials than the metallic ones, leading to greater profiles and hence increased weight. However, this influence was not included in the system model and was not quantified.

Kočí et al. [35], based on Kulhánek et al. [36], assume that the transportation and constructional phase together causes about 5% of overall buildings' impact on the environment. In the case of a regular building, the impact from the building operation is about 70%. Extrapolating from this data, construction and transportation phase of zero energy buildings with eliminated operational impact can cause about 17% of all environmental impacts whereas the material production phase ratio grows up to 67%.

The results of the assessment are shown in Fig. 10 and in Table 2. There was a difference apparent in all included indicators even in the first step of optimization. The B1 and B2 CWs' reduction in environmental indicators compared to the aluminium CW varied from 25% in EP (B1–A1) to 75% in embodied non-renewable energy (B2–A2). To arrive at an absolute reduction amount, the application of CW on a specific building would have to be calculated. Considering the production requirements (energy, raw materials, aluminium production plant, etc.) of the aluminium CW compared to the production of the materials and the elements used in the optimized variant (wood-based materials), it is likely that the transportation distance would be rather smaller for the new design thanks to the use of locally produced materials. As part of the further development, it was possible to take another step and to apply the design strategies once again to a technically proven and certified design. In some cases, a requirement for further development of elements has been encountered in order to reduce the environmental impact with the demand of other professions (for example, in the case of replacing aluminium laths with another material due to thermal bridges in the construction). This could not be done at the first prototype stage for a variety of reasons, such as cost and demand production, but it would be possible to achieve once in mass production.

All the results of the lifecycle assessment were, therefore, complemented by a third variant of the CW—a two-step optimized solution (C1 and C2), which shows the possibility of going even further in development. It used the blown cellulosic fibres as the main insulating layer instead of the wood fibre insulation and replaced said aluminium laths with PVC ones. Even though it is recycled material, the cellulose fibre insulation carries the environmental burden of its original product so that its impact on the calculation was found higher than that of the original wood wool. Unfortunately, its environmental benefits as a recycled material were not reflected in the assessed criteria. In spite of that, the changes allowed reaching a further reduction in all environmental indicators compared to both the original and new CW design. The embodied non-renewable energy was reduced in the C1 variant with a window to 39% of values of original aluminium CW (A1) and for the opaque panel in C2 variant even to 19% of the value of the A2 variant. The global warming potential (GWP 100a) indicator showed a major reduction in both new alternatives: 51% (B1), and 42% (C1) of original CW values (A1) and 29% (B2) and 21% (C2) of the value of the module in A2 variant.

Up to 10% of embodied energy and 12% of GWP 100a was consumed by the production of the steel anchoring elements. In future development, the use of optimized steel elements or a smaller amount of material can bring an additional reduction of environmental impact.

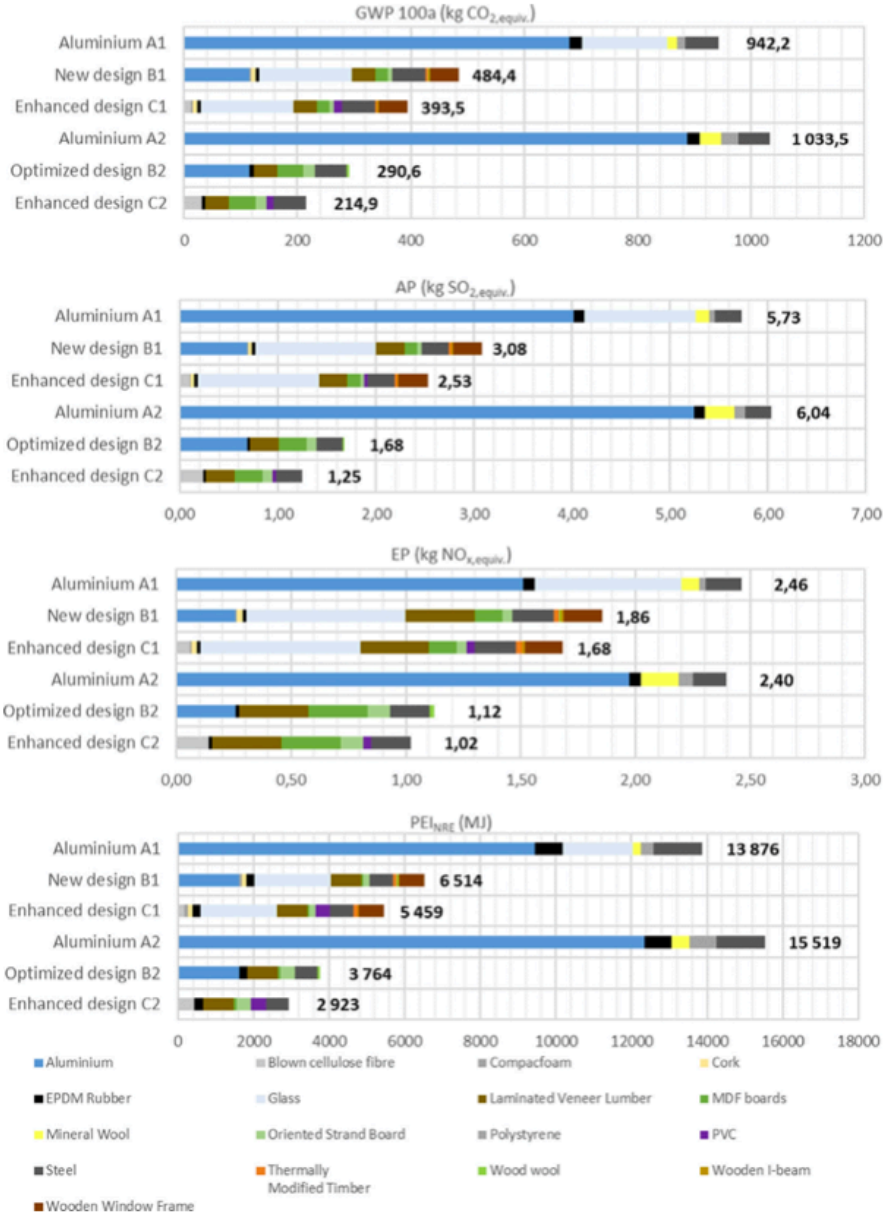


Fig. 10. Environmental parameters of the variants – a panel with a window A1-C1, opaque panel A2-C2, all with similar areas of 4.95 m^2.

For the variants with a window (A1, B1, and C1), the calculation was done for the CW module with triple glazing, which was included in all material alternatives similarly. It was obvious, though, that the difference can be larger in the case of opaque modules, where the major contribution of glazing does not appear.

4.6. Limitations of the study

The authors of the lifecycle study are aware of limitations related to the accuracy of the input data on environmental impacts, limitations arising from the level of detail of description of all lifecycle phases, and limitations related to the need for maintenance during the use phase.

In the input data on the environmental impacts, the study has to rely on publicly available data from EPDs and from Ecoinvent database. The differences in the methodologies in data collection and calculation are known and were analysed before, for instance, in [37].

The description of some lifecycle phases was only based on estimates as, at the time of writing the article, precise data were not available. For instance, we likened the assembly stage of modules in the factory to that of a traditional curtain wall panel solution, as we do not yet have the experience with serial production of the designed product. Also, we estimated the impacts of transportation to be lower than those of traditional panel CWS, as our system uses more local materials and thus reduces the transportation paths.

The lifetime of materials and elements is a crucial parameter influencing the overall environmental impact of any product. Knowledge about the need for maintenance during the use phase is limited as we do not have 40 years of experience from a real application. Nevertheless, we tested the designed product quite intensively. The durability of the specific materials used was tested in detail. The durability tests were performed at real climatic conditions so that the sufficient lifetime of the design can be ensured. The designed system has been monitored in the experimental facility for two years, closely for a third of the year. A seamless behaviour of the designed compositions under normal conditions had been confirmed (in the variant with aluminium laths). Moisture content by weight of the wooden elements was measured and it ranged from 11 to 15% during the year. The measurements revealed a weak point of the construction which was the installation of external windowsills. The water under a windowsill occurred twice during torrential rains. This subsequent moisture was spontaneously dried after 3 months to standard values. Based on these findings, the constructional solutions of the detail were modified. Also, the water- and airtightness tests were performed to ensure the desired quality of the inter-modular connections.

The designed solution was proven as durable and reliable for the application with a presumed identical lifetime compared to original CWs.

5. Conclusions

The process undergone to develop an environmentally efficient curtain wall for both refurbishments and new buildings was shown. The presented newly designed CW was carefully tested and the reduction of non-renewable embodied energy and GHG emissions were assessed.

The LCA in the early stage proved a high potential for the reduction of environmental burden by utilization of natural materials. The results of the experimental testing proved that the developed curtain wall system fulfilled the standard technical requirements and did not suffer when subjected to simulated or standard climatic conditions. By its properties, it can be used as a dependable substitute for the usual metallic curtain walls. The detailed LCA study showed that the fabrication of one panel with a window (B1) causes 49% less carbon emission and consumes 53% less primary energy compared to the aluminium-based alternative (A1). The design of the variant C1 enables further reduction of embodied carbon emissions by 10% and embodied primary energy by 8%. Significant reduction possibilities were also identified in acidification potential (46% reduction in new general design and 56% of reduction in enhanced design) and eutrophication potential (24% reduction in new general design and 32% of reduction in enhanced design).

For the opaque module, the savings were found to be even higher: 75% reduction for B2 module, 81% reduction for C2 in embodied non-renewable energy and 71% (B2) and 79% (C2) reduction in GWP 100a indicator compared to the A2 variant.

In addition to environmental comparison, further alternatives were described and compared: the fire-resistant alternative and the CW with improved acoustic parameters. With a fully fire-resistant alternative panel, the designed system is from the fire perspective variable and most fire-safety problems can be solved. However, it was later discovered that other alternative panels of CW, namely glazed fire-resistant panels or fire-barrier panel should be developed to satisfy the architectural design. The CW alternative with improved acoustic can cover the applications where the new design cannot be utilized.

It was shown that the assumptions and principles of building design strategies for the reduction of embodied primary energy and embodied emissions of greenhouse gases were valid and applicable for the CW design and consequent technical challenges had engineering solutions. It was also illustrated how various approaches to a lifecycle assessment of the same building element lead to various outcomes.

Acknowledgment

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Czech Building Stock: Renovation Wave Scenarios and Potential for CO_2 Savings until 2050

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Abstract: One of the major anthropogenic sources of greenhouse gases is the operation of building stock. Improving its energy efficiency has the potential to significantly contribute to achieving climate change mitigation targets. The purpose of this study was to roughly estimate such potential for the operation of the national building stock of Czechia to steer the national debate on the development of related national plans. The estimation is based on a simplified energy model of the Czech building stock that consists of sub-models of residential and nonresidential building stocks, for which their future energy consumptions, shares of energy carriers and sources, and emission factors were modeled in four scenarios. Uncertainties from the approximation of the emission factors were investigated in a sensitivity analysis. The results showed that the operation of the Czech building stock in 2016 totaled 36.9 Mt CO_2, which represented 34.6% of the total national carbon dioxide emissions. The four building stock scenarios could produce reductions in the carbon dioxide emissions of between 28% and 93% by 2050, when also considering on-side production from photovoltaics. The implementation of the most ambitious scenario would represent a drop in national CO_2 yearly emissions by 43.2% by 2050 (compared to 2016).

Keywords: national building stock; climate change mitigation; carbon dioxide; scenarios modelling; Paris Agreement; EU Green Deal; energy efficiency

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1. Introduction

1.1. Buildings and Climate Change

In the context of climate change mitigation, the world's nations are drafting and discussing their plans to achieve their national greenhouse gas reduction commitments [1–4]. The mitigation of climate change is featured in the strategic plans of the European Commission [5] and its member states. Czechia supports the EU target of complete carbon neutrality by 2050 and has committed to a reduction in national CO_2 emissions of 80–95% by 2050 compared with the base year 1990 [6]; however, a detailed national plan that describes practical measures in each segment of the national economy is not yet ready.

One of the major anthropogenic sources of greenhouse gases is the operation of buildings [7], so improving the energy efficiency of the building stock has the potential to significantly contribute to achieving the national climate change mitigation targets [8]. The efforts to exploit this potential span across scales, from the global perspective through the national building stock, building stocks of regions and cities, to the scale of a single building [9].

1.2. Background

At the scale of a single building, a growing body of literature is focused on the theory of reducing buildings' greenhouse gas (GHG) emissions. Some studies attempted to align the design of buildings with the intermediate goals of the Paris Agreement [10,11], and many papers report advances in zero-GHG buildings, including climate-neutral [12], carbon-neutral [13], and zero-emission [14–16] buildings. The various definitions and approaches were discussed at the 71st LCA Forum in 2019 [17] and recently summarized by Satola et al. [18], who analyzed the definitions and their respective emission performance targets. In the Nordic countries, GHG limits are already being introduced into building standards [19].

At the city level, efforts are concentrated on municipality-owned building stocks and policies for privately owned buildings in cities. There is an ongoing debate on how to set the balance of responsibilities among the actors [20]. Many climate-related activities are ongoing at the municipal level; in Europe, the most visible seems to be the Covenant of Mayors for Climate and Energy [21].

At the national building stock level, researchers have investigated the general potential for GHG reductions and explored various paths to align the GHG emission performance with the climatic goals of the Paris Agreement. Xing et al. [22] investigated the potential contribution of the Chinese residential sector to the nation's climatic contributions under various levels of carbon tax. The study took 2010 as the base year and modeled CO_2 emissions for 2020 and for 2030 in three scenarios of development. They found a potential to achieve CO_2 emission intensity reductions of 60–65% in the range of hypothetical situations corresponding to carbon emissions pricing between USD 44 and 58/t CO_2.

Yu et al. [23] modeled the building stock in India accounting for the evolution of the buildings sector, including changes in GDP, population, urbanization, floorspace expansion, growth in energy service demand, and choice among technologies and fuels for individual energy services. They found that implementing a wide range of energy efficiency policies can reduce the total Indian energy use by 22% and lower total Indian carbon dioxide emissions by 9% by 2050. Jeong [24] investigated four scenarios of development of the South Korean residential building sector between 2007 and 2030. They found that despite the expected strong demand for new residential developments, in one of the modeled scenarios, there was a potential for 12.9% CO_2 emissions reduction (compared with a 10.7% increase in the business-as-usual scenario). In Germany in 2013, Bürger [25] analyzed the GHG emissions of the national residential building stock in the context of the use of the development of building standards, heat supply technologies, and renewable energy potential. They analyzed three long-term scenarios of the German building stock development to 2050 and compared them with the emission budget then available for Germany. Based on the results, the authors urged for a swift implementation of additional strong climate protection measures. The work was further developed and described in Klimaneutraler Gebäudebestand 2050 [26,27], which simulated GHG emission reduction scenarios of −35%, −50%, and −65% by 2050.

Frischknecht et al. [28] conducted a complex analysis of the carbon footprint of the Swiss real estate sector. The findings showed that the use stage of buildings represents only two-thirds of the total GHG emissions in the sector, whereas an additional 30% is caused by the buildings' supply chains, stating that the relative significance of the embodied GHG is rising (which was also by an investigation of building case studies by Röck et al. [29]).

Kranzl et al. [30] analyzed GHG emission reduction scenarios from the policy-driven bottom-up model recently in place for European countries in eight EU and national projects (including data for Czechia), compared them amongst each other using various indicators, and analyzed whether the scenarios would lead to an achievement of GHG emission reductions in the range of 85–95% by 2050. The results showed that scenarios labelled as ambitious for several EU member states achieve GHG reductions of 56–96% by 2050. However, just 27% of these ambitious scenarios achieve reductions above 85%.

In Czechia, we [31] previously investigated five scenarios of the development of the Czech national building stock by modeling cumulative CO_2 emissions in the periods 2015–2030, 2031–2050, and 2051–2075, and compared them with the UN Emissions Gap Report [32]. It was based on previously developed models of energy consumption of the Czech residential and nonresidential building stocks, which also considered the future changes in climatic conditions due to climate change in two scenarios. Its most progressive scenario forecasted a reduction in the CO_2 emissions of 66% by 2075. None of the modeled scenarios was found to comply with the Paris Agreement.

Another publication that recently discussed the GHGs of the Czech buildings is the report Pathways to Decarbonize the Czech Republic [33]. It presents the cost-optimum decarbonization path for the state, including buildings, with a reduction in GHG emissions of 31% by 2030 and 97% by 2050.

1.3. Study Objectives

The study presented in this paper is a contribution to the ongoing national debate specifically focused on the national policies planned for regulating the energy efficiency of the Czech building stock (CBS). It was performed in collaboration with the Czech nongovernmental organization Chance for Buildings (CfB) and the University Centre for Energy Efficient Buildings of the Czech Technical University in Prague (UCEEB). CfB is an alliance of leading trade associations that supports energy-efficient and environmentally sustainable construction and renovation of buildings. It gathers the Czech Green Building Council, Passive House Centre, Mineral Insulation Manufacturers Association, EPS Association, and the Energy Service Providers Association. It represents over 300 companies across the entire value chain of building construction and renovation [34]. UCEEB is a multidisciplinary applied research center focused on promoting sustainable technical solutions in the built environment [35].

The objective of this work was to follow-up on our previous work and to quantify the approximate potential for CO_2 emission savings from the operation of the CBS according to the actual individual retrofitting scenarios prepared by CfB in accordance with the requirements of the long-term renovation strategy under Article 2a of the Energy Performance of Buildings Directive (EU) 2018/844, and evaluate the possible contribution of energy saving measures in the building stock to the national emission commitments considering the updated emission factors for electricity, heat from district heating systems, and future gas mix in gas pipelines.

2. Materials and Methods

The methods used in this study to model, calculate, and evaluate the potential for savings in the operational CO_2 emissions of the CBS included the following:

- Defining scenarios for the development of the CBS including starting state, especially in terms of area, quality, and expected rate of retrofitting, and increase in the number of new constructions;
- Processing of data on energy consumption in buildings for the period up to 2050 (details on the data modeling are provided in Section 2.1.2);
- Defining scenarios of shares of energy sources in future energy consumption for heating, hot water, and lighting in buildings, in line with the consumption stated in energy certificates;
- Adding estimates of energy consumption for appliances and cooking in the residential sector;
- Identifying the CO_2 emission factors for individual fuels and energy carriers;
- Calculating operational CO_2 emissions of CBS for individual building retrofitting scenarios;
- Defining scenarios for the development of photovoltaic installations and variant modeling of CO_2 emissions;
- Conducting a sensitivity analysis considering the future decrease in emission factors of electricity from the national grid, heat from district heating systems, and gas from the distribution network;

- Calculating the share of the CBS on the national operational CO_2 emissions and its theoretical share in 2050;
- Evaluating results with regard to the national climate commitments.

2.1. Definition of the Czech Building Stock Development Scenarios and Summarizing the Corresponding Energy Consumption

This study was based on four construction-technical scenarios for the retrofitting of the CBS. For each of them, partial scenarios were modeled, differing in the structure of energy sources in buildings.

The following sections describe the origin of the base data of the composition of the CBS; the modeling of the final energy consumption of the CBS; four scenarios of the depth and pace of energy retrofitting; the projection of the shares of energy carriers on the final energy consumption in the four scenarios; and the forecast of the development of the building-attached and building-integrated photovoltaics (BIPV).

2.1.1. Origin of the Base Data on Composition of the CBS

The data on the composition of the CBS were obtained from several previous reports published by Chance for Buildings, especially Investigation of the Czech Residential Building Stock and Potential for Savings [36], Investigation of the Czech Non-Residential Building Stock and Potential for Savings [37], Strategy for Retrofitting of Buildings [38], its 2016 update [39], and Long-Term Renovation Strategy of the Czech Building Stock—update May 2020 [40]. The data for these reports originated from various datasets provided by the Czech Statistical Office, especially data from the national 2011 census, the statistical survey on buildings called ENERGO 2015, and a statistical survey on buildings called Budovy 1–99 from 2018. The basic data on the composition of the CBS are similar to those used in the previous study [31].

2.1.2. Modeling of the Final Energy Consumption of the CBS

The base energy model of the CBS was created in 2016; hence, 2016 was the base year for which the statistical data were collected. The energy model is composed of sub-models of the residential and nonresidential building stocks. It was used to provide forecasts of yearly total final energy consumptions of Czech residential and nonresidential buildings between 2016 and 2075; in this study, we used datasets toward 2050.

For the energy simulations of existing residential building stock [36] (see Appendix A for more details), we used a stochastic energy model that calculated the energy demand for the heating of a set of 1000 simulated buildings, which was created from data samples of buildings divided into 78 categories by typology, size, and age based on the statistical data. The calculations in a custom-made tool (MS Excel sheets and macros) followed the rules given by EN ISO 13790 and applied the boundary conditions used normally when calculating energy performance certificates according to national rules. Statistical data provided the input for the estimation of the proportion of residential building stock that had already undergone energy retrofitting, estimated as 35% in 2016. The report presents the calibration of the energy model according to the available statistical data on the final energy consumption of building stock made by comparison of the calculated (52,896 GWh/year) to statistical data provided by the Ministry of Industry and Trade of the Czech Republic (47,798 GWh/year). The calibration of the model to the statistical data was made by decreasing the considered indoor air temperature. An English summary of the report is provided in Appendix A below.

The energy modeling of existing nonresidential building stock [37] (English summary of the report is provided in Appendix B below) was based on a sample of 100 nonresidential buildings with detailed energy simulations and an additional sample of 20 existing buildings with detailed data on real energy consumption. The building typologies included in the study were office buildings, administrative buildings, commercial buildings, educational buildings, cultural buildings, hotels, restaurants, medical facilities, sports facilities, storage buildings, and those with mixed use. A list of them and sample photos are presented in the report [37], where Section 2.1 describes the geometrical characteristics of the sample. Section 2.3 describes the outcomes of the energy modeling, which was processed in line with the national Decree 78/2013 Coll. used for the calculation of the energy performance certificates of buildings (the baseline scenario is provided in the charts and tables labelled as SS and visualized in black). The resulting data on energy demand and final energy consumption are provided from page 13 onward. The calibration of the energy model was made by comparison of the simulated energy consumptions with the real energy consumptions of twenty existing buildings. Based on these comparisons, we derived a correction formula for their extrapolation on the whole nonresidential building stock. It was based on a sensitivity analysis that identified the key parameters: surface area/volume ratio, ratio between the mean U-value and the reference U-value used in the declaratory energy performance calculation method, mean indoor temperature and the overall efficiency of the heating system.

The simulated energy consumptions were extrapolated to the whole Czech nonresidential building stock using national statistical data on the proportions of each type of building in the whole building stock.

The energy model considers various depths of energy retrofitting measures; their combination is described further in the sections dedicated to scenarios.

Residential buildings statistically retrofitted to a low-energy standard and without retrofitting were simulated using construction interventions leading to the reduction in energy demand for heating and the improved efficiency of heating due to the replacement of heat sources. The potential savings from the preparation of domestic hot water and lighting were simulated separately.

The modeled nonresidential buildings that were in lower-than-current energy standards were simulated using various combinations of energy-saving interventions such as: partial improvement in thermal characteristics of building envelopes; complex retrofitting actions on building envelopes as a whole; replacements of heat sources; installations of mechanical ventilation systems with heat recovery; installation of new renewable energy systems.

2.1.3. Four Scenarios of the CBS Development by the Depth and Pace of Energy Retrofitting

For this study, we defined the four scenarios of the future development of CBS (Table 1):

- Baseline Scenario, which corresponds to the state-of-the art policy without any improvements (business as usual);
- Governmental Scenario, proposed in the Long-Term Renovation Strategy Supporting Renovations of the National Residential and Nonresidential Public and Private Building Stock published by the Czech Ministry of Industry and Trade, which is responsible for energy and construction policies [41];
- Progressive Scenario (deep retrofitting of CBS);
- Hypothetical Scenario (fast deep retrofitting of CBS).

The scenarios were defined with the help of the following variables:

- Annual retrofitting rates: the percentage of building stock that undergoes retrofitting each year (by building category; Table 2).
- Retrofitting depths: In the context of the study, shallow retrofitting means that the building envelope is upgraded to required U-values aligned with the national standard ČSN 73 0540; moderate indicates the recommended U-values are met; deep indicates the U-values prescribed for passive houses and equipment of the building with a mechanical ventilation with heat recovery. Table 1 provides further insights into the typical U-values by the depths of retrofitting. The lower part of Table 2 shows the distribution of the renovated building floor area by the retrofitting depths. Figure 1 visualizes the scenarios.

Table 1. The retrofitting depths by the considered U-values of the main building compositions and ventilation systems for nonresidential building stock energy modeling.

Type of Structure	**Retrofitting Depths**		
	Shallow	**Moderate**	**Deep**
Thermal quality of building envelope			
	Select typical U-values of the main building compositions in $W/(m^2 \cdot K)$		
External walls	0.30	light 0.25, heavy 0.20	0.15
Roofs	0.24	0.16	0.10
Floor below attic without thermal insulation	0.30	0.20	0.12
Floor structures above exteriors	0.24	0.16	0.12
Floor structures above unheated underground floors	0.60	0.40	0.25
Windows	1.50	1.20	0.90
Doors	1.70	1.20	0.90
Ventilation			
Ventilation system	Natural ventilation or mechanical ventilation without heat recovery	Natural ventilation or mechanical ventilation without heat recovery	Mechanical ventilation system with heat recovery (efficiency $\eta_{H,hr,sys}$ = 60% according to EN 308)

Table 2. Definition of the four scenarios of the development of the Czech building stock (CBS).

Building Categories	**Retrofitting Depth**	**Scenario**			
		Baseline	**Governmental**	**Progressive**	**Hypothetical**
New construction and demolition: annual increase in floor area *					
Residential—single family houses		1.11%	1.11%	1.11%	1.11%
Residential—multifamily houses		0.46%	0.46%	0.46%	0.46%
Nonresidential		0.96%	0.96%	0.96%	0.96%
Annual retrofitting rates by category (percentage of building stock that undergoes retrofitting each year)					
Residential—single family houses		1.40%	1.40%	3.00%	3.00%
Residential—multifamily houses		0.79%	0.79%	2.00%	3.00%
Nonresidential		1.40%	2.00%	2.50%	3.00%
Distribution of the renovated building floor area by retrofitting depths and their time distribution					
Shares of retrofitting depths by building categories		Default shares, stable for whole period **	Linear increase from default until 2025, then stable	Linear increase from default until 2025, then stable	Hypothetical leap in 2020 and then stable
Residential: single-family houses	Shallow	35%	20%	5%	5%
	Moderate	38%	40%	10%	10%
	Deep	27%	40%	85%	85%
Residential: multifamily houses	Shallow	31%	20%	5%	5%
	Moderate	50%	40%	10%	10%
	Deep	19%	40%	85%	85%
Nonresidential	Shallow	27%	20%	5%	5%
	Moderate	44%	40%	10%	10%
	Deep	30%	40%	85%	85%

* Considered demolition rates: single-family houses 0.2%, multifamily houses 0.1%, nonresidential buildings 0.2%. ** Default shares of retrofitting depths from the ENEX database, which collects data from the energy certificates listed for the purpose of "Major renovation of existing building", taken from [41].

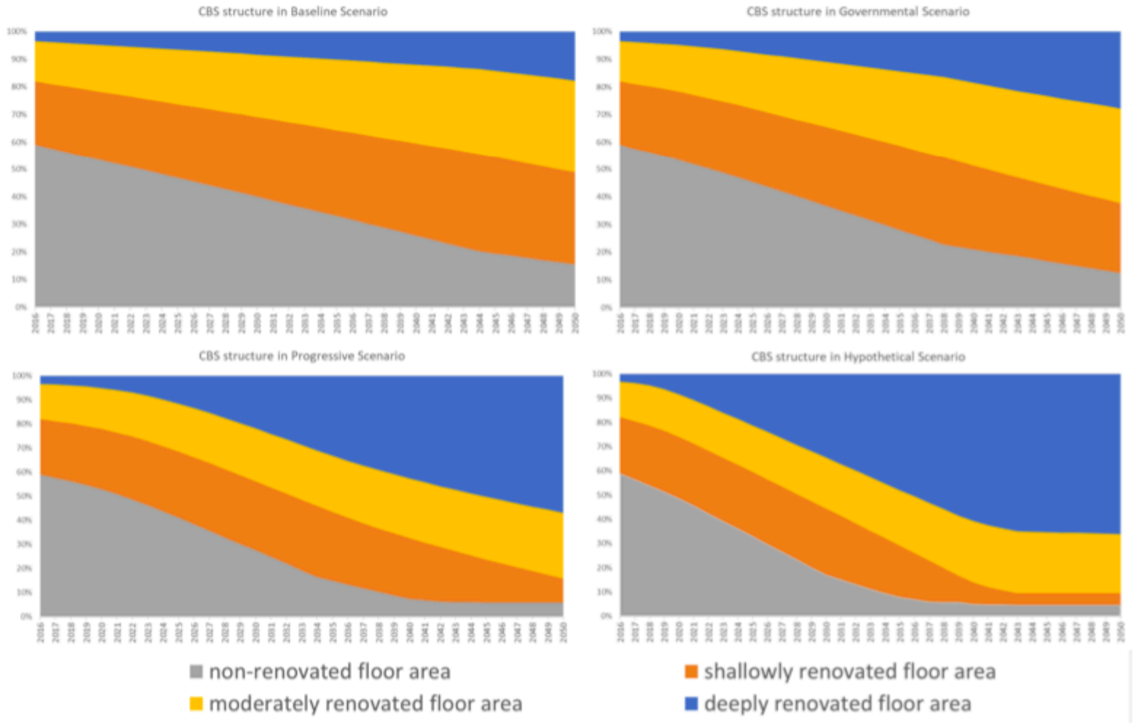

Figure 1. Modeled shares of the nonrenovated, shallowly renovated, moderately renovated, and deeply renovated buildings in the whole CBS (by buildings' floor area).

From the energy model, we obtained the yearly final energy consumption for residential and for nonresidential building stocks between 2016 and 2050. Table 3 shows the selected figures.

Table 3. A simplified overview of the final energy annual consumptions in PJ obtained from the energy model that was used for the modeling of the carbon dioxide emissions of the CBS.

Scenario	2016	2030	2040	2050
Residential building stock				
Baseline	253	234	219	204
Governmental		232	214	196
Progressive		206	154	126
Hypothetical		179	126	115
Nonresidential building stock				
Baseline	125	117	109	102
Governmental		113	102	93
Progressive		107	94	86
Hypothetical		98	85	83

As the energy model used for residential buildings excluded energy consumption for cooking and home appliances, they were added at the end in the annual amount of 15.5 PJ for home appliances (in electricity) and 15.0 PJ for cooking (equal share of electricity and natural gas). These values were constant for each modeled year.

2.1.4. Projection of the Shares of Energy Carriers on the Final Energy Consumption in the Four Scenarios

The projections of the shares of the energy carriers were defined separately for the residential and nonresidential building stock for the years 2016 and 2050, and values for the intermediate years were linearly interpolated. The base values for 2016 were defined by the analysis of sources from the Czech Statistical Office listed above. The values for 2050 were defined using national energy commitments by analyzing national policy documents published recently by the Czech Ministry of Industry and Trade, especially The National Energy and Climate Plan of the Czech Republic [6]. The definition of the share of renewables was based on the reports by the Czech Chamber of Renewable Energy Sources dealing with the renewable energy sources potential in buildings and on Czechia on Way towards Carbon Neutrality [42]. The considered shares of the energy carriers and sources are summarized in Table 4. Photovoltaics are discussed in the next section.

Table 4. Considered shares of energy carriers and sources on the final energy consumption in the four scenarios.

Scenario		**Baseline**	**Governmental**	**Progressive**	**Hypothetical**
Energy Carrier/Source	**2016**	**2050**	**2050**	**2050**	**2050**
Residential building stock					
Fuel oils	0%	0%	0%	0%	0%
Natural gas	30%	25%	26%	23%	22%
Coal	12%	10%	3%	0%	0%
Biomass (excluding pellets)	20%	25%	20%	15%	12%
Pellets	0.3%	4%	9%	14%	16%
District heating	17%	16%	16%	15%	15%
Electricity	19%	10%	11%	8%	8%
Solar thermal	0.3%	2%	4%	6%	7%
Heat pumps	1%	9%	12%	19%	21%
Nonresidential building stock					
Gas cogeneration	2%	2%	2%	2%	2%
Natural gas	27%	26%	23%	22%	22%
Coal	0.2%	0.2%	0%	0%	0%
Biomass (excl. pellets)	0%	0%	0%	0%	0%
Pellets	0.3%	4%	8%	8%	9%
District heating	29%	28%	25%	25%	25%
Electricity	42%	39%	36%	36%	35%
Solar thermal	0.2%	2%	4%	4%	4%
Heat pumps	0%	0.2%	3%	3%	3%

2.1.5. Forecast of the Development of the BIPV

Scenarios for the electricity produced from BIPV differ within the scenarios. The basic difference is the depth of the retrofitting: the deeper the retrofitting, the greater the assumption of preference for more complex projects and thus the installation of a photovoltaic system. The scenarios were paired with the scenarios from the document Potential for utilization of renewable energy sources in buildings (2018) provided by Czech Chamber of Renewable Energy Sources, which explored the technical potential for BIPV. It started from the optimum orientation and slope, which is in Czechia south facing area with 35° inclination. For BIPV installation, areas of roofs that have a reduction in the energy yield lower than 20% and walls lower than 40% compared to the optimum position were considered, and the maximum usable area on roofs for BIPV is considered as 40% and only 20% of the south facing walls' area. It was also assumed that 30% of buildings are not suitable for PV installation at all due to shading by vegetation, other buildings or because of legal restrictions or heritage protection. The considered efficiency of the PV panels was 18%. The resulting production of electricity from BIPV is shown in Table 5.

Table 5. Considered yearly amount of electricity production in GWh from building-attached and building-integrated photovoltaics. The values for the intermediate years were linearly interpolated.

Sector	Scenario	2016	2030	2040	2050
Residential	Baseline and Governmental	262	2944	4710	6477
	Progressive	262	5561	8995	12,430
	Hypothetical	262	5414	9707	14,000
Nonresidential	Baseline and Governmental	140	1560	2490	3420
	Progressive	140	2940	4755	6570
	Hypothetical	140	3129	5265	7400
Whole building stock	Baseline and Governmental	402	4504	7200	9897
	Progressive	402	8501	13,750	19,000
	Hypothetical	402	8543	14,971	21,400

2.2. Calculations of CO_2 Emissions in Scenarios

The calculations procedure for the amounts of CO_2 emissions included these steps:

- Taking the input yearly datasets for total energy consumption for residential and nonresidential building stock in the four scenarios (data for 2016, 2030, 2040, and 2050 are shown in Table 3);
- Distributing the total energy consumption per energy carrier and energy source according to Table 4;
- Allocating the electricity production from BIPV for each year according to Table 5;
- Multiplying the energy consumption by the corresponding emission factor (below);
- Totaling the resulting emissions for each year in the four scenarios.

Assumptions about the Emission Factors

The CO_2 emission factors for fuels were obtained from the National Inventory Report [43,44]. For the emission factor of the electricity from the grid, no single official number was available. On the basis of an analysis of available sources [45–47] and consultations with the representatives of the Ministry of the Environment, we set the emission factor as 0.6 t CO_2/MWh.

Deciding on a single emission factor for the heat from district heating systems is difficult because the emission factors are locally specific and the used fuels also depend on the efficiency of the heat source, system losses, and, in case of cogeneration, on the allocation of the produced emissions among the produced (and sometimes wasted) heat and electricity. We considered various sources of relevant information [48–51]; for the heat from the district heating systems, we selected a value of 0.3 t CO_2/MWh.

The emissions from gas cogeneration units were roughly proxied by halving the emission factor of the combustion of natural gas. In the calculations of the emissions from heat pumps, we considered an average coefficient of performance 3.0 and electricity from the grid as the energy carrier (so the resulting emission factor was one-third the electricity emission factor).

We assumed that the electricity produced onsite from BIPV will save electricity that would otherwise have had to be produced by the centralized sources supplying power to the national electricity grid. Therefore, we multiplied the energy produced from photovoltaics by the emission factor for the grid electricity and subtracted them from the totals for each year.

For the biomass, in line with the Czech methods for energy auditing, we assumed sustainable forest stewardship and simplification leading to a zero emission factor. Similarly, a zero emission factor was applied to the heat from the solar thermal collectors (not considering the embodied impacts and neglecting the needed auxiliary energy).

The CO_2 emission factors applied in the calculation are summarized in Table 6.

Table 6. CO_2 emission factors applied in the calculations in metric tonnes of CO_2/MWh. BIPV, building-integrated photovoltaics.

Fuel or Energy Carrier	Assumed Emission Factor (t CO_2/MWh)
Coal	0.35
Fuel oils	0.26
Natural gas	0.20
Biomass	0.00
Heat from solar collectors	0.00
Electricity from the national grid	0.60
Onsite-produced electricity from BIPV	(−)0.60
Heat from district heating system	0.30
Energy from gas cogeneration (proxy)	0.10
Heat from heat pumps	0.20

Due to the uncertainties regarding emission factors and the assumptions of future reduction in some of them with the expected decarbonization of the Czech energy sector, a sensitivity analysis was performed, as described below.

2.3. Sensitivity Analysis Considering the Future Decrease in Emission Factors of Electricity from the National Grid, Heat from District Heating Systems, and Gas from Distribution Network

Due to the uncertainties regarding the emission factors for electricity, district heat, and the possible future development of the gas mix, a sensitivity analysis was performed for 2050. The sensitivity analysis was performed both without and with consideration of BIPV. Notably, we did not analyze the technical or legal potential of the emissions factors—it was performed only to show what-if scenarios.

The effects of the potential reduction in emission factors were examined separately:

For electricity from the grid, a reduction in emission factors of 67% and 33% was applied, from the initial value of 0.6 to 0.4 and 0.2 t CO_2/MWh. This considers the possible future decarbonization of the electricity grid (at the utility level). For district heating, a reduction in emission factors of 75% and 50% was used, i.e., from the initial value of 0.3 to values of 0.225 and 0.15 t CO_2/MWh. This considers the possible future exchange of coal resources for gas or biomass. For distribution gas, a reduction in the emission factor of 90% and 80% was used, i.e., from the initial value of 0.2 to 0.18 and 0.16 t CO_2/MWh. This reflects the possible future injection of biogas into the distribution system, or syngas produced with the help of low-emission electricity.

In the second step, these emission factor reductions were assigned to two variant scenarios of emission factors' reductions, as described in Table 7.

Table 7. Variant scenarios for CO_2 emission factors (EFs) applied in the sensitivity analysis for electricity, heat from district heating systems, and gas from gas distribution systems for the year 2050 in metric tonnes of CO_2/MWh.

Fuel or Energy Carrier	Emission Factors for Variant Scenarios for 2050 (t CO_2/MWh)		
	EF1 (Baseline)	EF2	EF3
Electricity from grid	0.600	0.400	0.200
Heat from district heating system	0.300	0.225	0.150
Gas from gas distribution system	0.200	0.180	0.160

2.4. Evaluating Results Regarding National Climate Commitments

To evaluate the results of the study with respect to national climate commitments, we needed to summarize the input data related to the national climate commitments. In its Climate Protection Policy, the Czech Republic has committed to reducing greenhouse gas emissions at least by 80% compared with 1990 [52]. Recently, the Czech government supported the carbon neutrality of the EU as a whole by 2050 and articulated the willingness to commit to a national reduction of 95% by 2050, but this statement has not yet been materialized into any national policy. According to *the National Energy and Climate Plan of the Czech Republic* [6], the Czech Republic produced a total of 194.35 Mt $CO_{2,eq}$ in 1990 (without considering LULUCF and waste). By 2016, these emissions had fallen to 124.02 Mt $CO_{2,eq}$. Compliance with the commitment will necessitate a reduction in annual emissions to 38.87 Mt $CO_{2,eq}$.

In this study, the complete localized emission factors for the global warming potential (GWP (t $CO_{2,eq}$)) were not available; therefore, only emissions of carbon dioxide were considered. The National Inventory Report of the Czech Republic from 2020 [43] provides an overview of the production of greenhouse gases by individual gases. For CO_2 emissions in the Czech Republic in 1990, it states a value of 164.2 Mt. If we consider the theoretically even distribution of the national commitment among the monitored greenhouse gases and sectors (applying the even contraction approach), the commitment means an 80% reduction in the CO_2 production by 2050 of a maximum of 32.8 Mt. In 2016, this production was 106.6 Mt CO_2, so by 2050, it is necessary to reduce the annual production of Czech emissions by another 73.8 Mt CO_2.

The results of this study showed that the building stock produced a total of 36.9 Mt CO_2 in 2016, which means that the operation of the building stock accounted for approximately 34.6% of total national emissions. The maximum target value needed to meet the adequate national emission commitment allocated to the building stock is 11.4 Mt CO_2 for 2050.

For 1990, emissions from the building stock could be retrospectively estimated as 67.25 Mt CO_2 (but this estimate is highly inaccurate; emissions fell sharply in the early 1990s mainly due to the downturn in heavy industry and economic restructuring).

3. Results

3.1. Results of the Calculated CO_2 Emissions by Scenario

The resulting emissions by scenarios are shown in the following tables. Table 8 shows the emissions achievable through energy-efficient retrofitting of buildings for each individual scenario, i.e., improving the quality of building envelopes, replacing resources with more efficient ones, and using efficient control systems and mechanical ventilation with heat recovery, but without the installation of photovoltaic systems. Table 9 also includes BIPV. For the sake of simplicity, the tables do not show values for each year between 2016 (which was the base year of the energy model) and 2050, but only for 2016, 2030, 2040, and 2050.

Table 8. Resulting CO_2 emissions from the operation of the Czech building stock for individual scenarios without considering BIPV. The values are given in Mt CO_2/year.

Segment	**Scenario**	**Year**			
		2016	**2030**	**2040**	**2050**
Residential	Baseline	23.2	20.3	18.2	16.2
	Governmental		19.7	17.2	14.9
	Progressive		17.5	13.0	10.4
	Hypothetical		15.8	11.4	9.9
Nonresidential	Baseline	13.7	12.5	11.5	10.5
	Governmental		11.7	10.1	8.9
	Progressive		11.1	9.3	8.1
	Hypothetical		10.1	8.3	7.7
Whole building stock	Baseline	36.9	32.8	29.6	26.7
	Governmental		31.4	27.3	23.8
	Progressive		28.5	22.3	18.5
	Hypothetical		26.0	19.8	17.7

Table 9. Resulting CO_2 emissions from the operation of the Czech building stock for individual scenarios considering onsite electricity production from BIPV. The values are given in Mt CO_2/year.

Segment	Scenario	Year			
		2016	2030	2040	2050
Residential	Baseline	23.1	18.5	15.3	12.3
	Governmental		17.9	14.4	11.0
	Progressive		14.1	7.6	2.9
	Hypothetical		12.6	5.6	1.5
Nonresidential	Baseline	13.6	11.5	10.0	8.4
	Governmental		10.8	8.6	6.8
	Progressive		9.3	6.5	4.2
	Hypothetical		8.3	5.2	3.3
Whole building stock	Baseline	36.7	30.0	25.3	20.8
	Governmental		28.7	23.0	17.8
	Progressive		23.4	14.0	7.1
	Hypothetical		20.8	10.8	4.8

The results of the calculation show the potential for reducing the operating CO_2 emissions of the CBS until 2050 without considering photovoltaics in the range between approximately 27.6% in the Baseline Scenario and 52.0% in the Hypothetical Scenario, compared with 2016. Including BIPV enables a total reduction in CO_2 emissions ranging from 43.6% to 86.9%. The results are visualized in Figure 2.

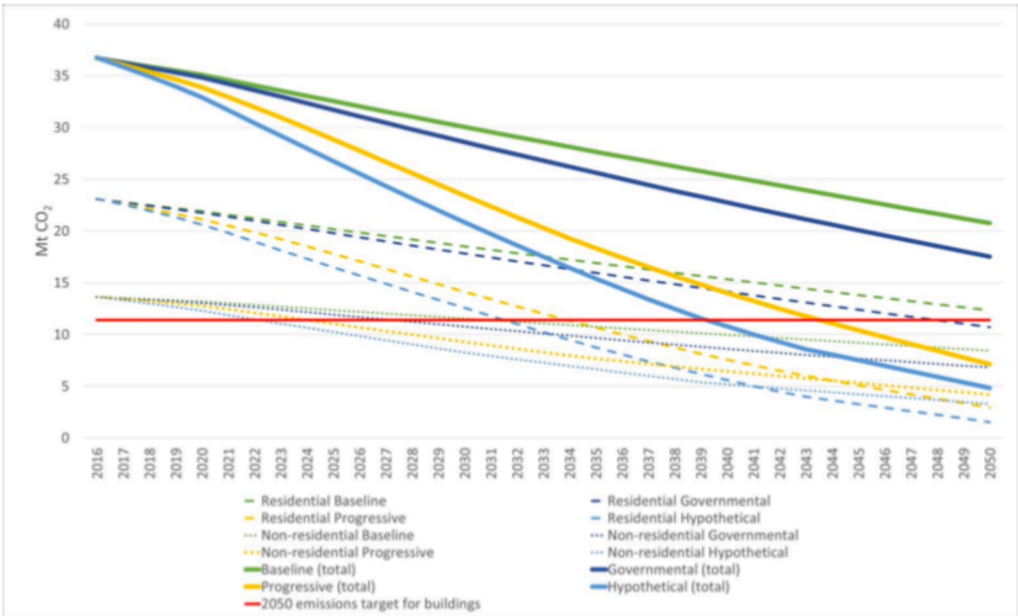

Figure 2. Modeled development of the amount of operational CO_2 emissions of the Czech building stock, including the consideration of BIPV (considered constant emission factors, in Mt CO_2). The dotted lines represent nonresidential building stock, the dashed lines represent residential building stock, and the solid lines show totals for the whole CBS. The red line represents the 2050 emission target for the whole CBS.

3.2. Results of the Sensitivity Analyses by Scenario

The following tables show the results of the sensitivity analysis of the values of operational CO_2 emissions in 2050. Tables 10–12 show the sensitivity to the emission factors of electricity from the grid, from the distribution, and from district heating, respectively.

The sensitivity to combinations of emission factors according to the combined variants EF1–EF3 is listed in Table 13.

Table 10. Sensitivity of the resulting CO_2 emissions from the operation of the CBS to the value of the electricity emission factor in 2050 for individual scenarios. Values are given in Mt CO_2/year.

Electricity		**Without BIPV**			**With BIPV**		
Electricity Emission Factor (t CO_2/MWh)		**0.6 (Baseline)**	**0.4**	**0.2**	**0.6 (Baseline)**	**0.4**	**0.2**
Residential	Baseline	16.2	13.4	10.6	12.3	10.8	9.4
	Governmental	14.9	12.0	9.2	11.0	9.5	7.9
	Progressive	10.4	8.1	5.9	2.9	3.2	3.4
	Hypothetical	9.9	7.7	5.5	1.5	2.1	2.7
Nonresidential	Baseline	10.5	8.3	6.1	8.4	6.9	5.4
	Governmental	8.9	7.0	5.1	6.8	5.6	4.4
	Progressive	8.1	6.4	4.6	4.2	3.8	3.3
	Hypothetical	7.7	6.1	4.4	3.3	3.1	2.9
Whole building stock	Baseline	26.7	21.7	16.7	20.8	17.8	14.8
	Governmental	23.8	19.0	14.2	17.8	15.1	12.3
	Progressive	18.5	14.5	10.5	7.1	6.9	6.7
	Hypothetical	17.7	13.8	9.9	4.8	5.2	5.6

Table 11. Sensitivity of the resulting CO_2 emissions from the operation of the CBS to the value of the emission factor of gas from the distribution system in 2050 for individual scenarios. Values are given in Mt CO_2/year.

Gas		**Without BIPV**			**With BIPV**		
Gas Emission Factor (t CO_2/MWh)		**0.2 (Baseline)**	**0.18**	**0.16**	**0.2 (Baseline)**	**0.18**	**0.16**
Residential	Baseline	16.2	15.9	15.6	12.3	12.0	11.7
	Governmental	14.9	14.6	14.3	11.0	10.7	10.4
	Progressive	10.4	10.2	10.0	2.9	2.7	2.5
	Hypothetical	9.9	9.8	9.6	1.5	1.4	1.2
Nonresidential	Baseline	10.5	10.3	10.2	8.4	8.3	8.1
	Governmental	8.9	8.8	8.6	6.8	6.7	6.6
	Progressive	8.1	8.0	7.9	4.2	4.1	4.0
	Hypothetical	7.7	7.6	7.5	3.3	3.2	3.1
Whole building stock	Baseline	26.7	26.2	25.8	20.8	20.3	19.8
	Governmental	23.8	23.3	22.9	17.8	17.4	17.0
	Progressive	18.5	18.2	17.9	7.1	6.8	6.5
	Hypothetical	17.7	17.4	17.1	4.8	4.6	4.3

Table 12. Sensitivity of the resulting CO_2 emissions from the operation of the CBS to the value of the emission factor of heat from the district heating systems in 2050 for individual scenarios. Values are given in Mt CO_2/year.

District Heating		**Without BIPV**			**With BIPV**		
Heat from District Heating System Emission Factor (t CO_2/MWh)		**0.300 (Baseline)**	**0.225**	**0.150**	**0.300 (Baseline)**	**0.225**	**0.150**
Residential	Baseline	16.2	15.6	14.9	12.3	11.7	11.0
	Governmental	14.9	14.3	13.6	11.0	10.4	9.8
	Progressive	10.4	10.0	9.6	2.9	2.6	2.2
	Hypothetical	9.9	9.6	9.2	1.5	1.2	0.8
Nonresidential	Baseline	10.5	9.9	9.3	8.4	7.8	7.2
	Governmental	8.9	8.4	7.9	6.8	6.3	5.9
	Progressive	8.1	7.7	7.2	4.2	3.7	3.3
	Hypothetical	7.7	7.3	6.9	3.3	2.9	2.4
Whole building stock	Baseline	26.7	25.4	24.2	20.8	19.5	18.3
	Governmental	23.8	22.7	21.6	17.8	16.7	15.6
	Progressive	18.5	17.7	16.9	7.1	6.3	5.5
	Hypothetical	17.7	16.9	16.1	4.8	4.1	3.3

Table 13. Sensitivity of the resulting CO_2 emissions from the operation of the CBS to the combination of the improved emission factors in 2050 for individual scenarios. Values are given in Mt CO_2/year.

Combinations		**Without BIPV**			**With BIPV**		
Emission Scenario		**EF1 (Baseline)**	**EF2**	**EF3**	**EF1 (Baseline)**	**EF2**	**EF3**
Residential	Baseline	16.2	12.5	8.7	12.3	9.9	7.4
	Governmental	14.9	11.1	7.3	11.0	8.5	6.0
	Progressive	10.4	7.5	4.7	2.9	2.6	2.2
	Hypothetical	9.9	7.2	4.4	1.5	1.6	1.6
Nonresidential	Baseline	10.5	7.5	4.6	8.4	6.2	3.9
	Governmental	8.9	6.4	3.9	6.8	5.0	3.2
	Progressive	8.1	5.8	3.5	4.2	3.2	2.2
	Hypothetical	7.7	5.6	3.4	3.3	2.6	1.9
Whole building stock	Baseline	26.7	20.0	13.3	20.8	16.0	11.3
	Governmental	23.8	17.5	11.1	17.8	13.5	9.1
	Progressive	18.5	13.4	8.2	7.1	5.8	4.4
	Hypothetical	17.7	12.7	7.8	4.8	4.2	3.5

3.3. Evaluation of Results from the Perspective of Emissions Targets

The results of the calculations showed that the modeled building stock produced a total of 36.9 Mt CO_2 in 2016, with 23.3 Mt CO_2 originating from residential buildings and 13.7 Mt CO_2 from nonresidential buildings. The total floor area of the buildings in 2016 was 599.49 million m^2, and the mean emission intensity for the entire building stock was 61.6 kg $CO_2/m^2 \cdot$year.

In the same year, 2016, the national emissions amounted to 106.6 Mt CO_2, which means that the share of the operation of the building stock in total national emissions was approximately 34.7%. The share of residential buildings in national emissions was approximately 21.9% and that of nonresidential buildings was 12.9%.

As for the accuracy of the provided results, the emission calculations of the baseline scenario were based on energy consumption data from the energy model that was calibrated to the available national statistics as described in Section 2.1.2 and on the emission factors shown in Table 6. Thus, the inputs on the energy inputs were as precise as possible; on the other hand, there is a source of uncertainties in the emission factors of the electricity from the grid and in the emission factor of the heat from district heating systems (which were both represented by just one figure).

The national commitment converted to CO_2 emissions in 2050 represents the total production of emissions as 32.8 Mt CO_2. For simplification, if we assume an even distribution of responsibility for reducing emissions across the sectors of the Czech economy, we can consider a constant share of national emissions for the building stock. This would mean that the target maximum annual CO_2 emissions of the building stock in 2050 would be 11.4 Mt CO_2. The expected floor area of buildings in 2050 was estimated at 741.02 million m^2, so the target emission intensity of the building stock to meet the national commitment was calculated as 15.4 kg $CO_2/m^2 \cdot$year, which is one-fourth compared with 2016.

The comparison of the emission values in individual scenarios listed in Tables 7 and 8 with the maximum target value needed to meet the national emission commitment of 11.4 Mt CO_2 showed that the commitment can only be met by implementing the Progressive Scenario at least for the retrofitting of buildings in combination with the development of photovoltaics.

In the Hypothetical Scenario, the target would be met as early as 2040, and in 2050, it would be close to the commitment to fully decarbonize the Czech building stock.

The Baseline scenario does not lead to a sufficient reduction: it reaches almost twice the value of the target for 2050. The Governmental Scenario then exceeds the target value by 56%.

To meet the Czech Republic's emission commitment, it is necessary to reduce the annual national production of emissions by 73.8 Mt CO_2 by 2050. If the Hypothetical Scenario considering photovoltaics is implemented, the building stock would save 31.9 Mt CO_2

per year, which would contribute a total of 43.2% to the reduction at the national level, i.e., a higher share than current emissions from buildings in total emissions.

In the Hypothetical Scenario without the development of photovoltaics, if the emission factor of electricity from the grid is reduced by 33% to 0.4 t CO_2/MWh, the emissions of the CBS will decrease by 22.0% by 2050 compared with the model with a constant emission factor. In the case of a reduction of 67% to 0.2 t CO_2/MWh, the decrease would be approximately 44.0%. A reduction in the emission factor of the heat from district heating systems by 25% or 50% would reduce the emissions by 4.5% or 9.0%, respectively. A reduction in the gas emission factor by 10% or 20% would result in a drop in the carbon dioxide emissions by 1.7% and 3.4%, respectively. In the case of a reduction in emission factors according to the EF2 combination of emission factors, the reduction in emissions would be 28.2%; EF3 would result in a 56.5% decrease in emissions.

In cases where BIPV is included and the deduction of theoretically excess electricity is compared with the electricity emission factor from the grid, the situation is less clear, because the higher the reading, the higher the electricity emission factor, and the faster the development of photovoltaics. In practice, this means that as the electricity emission factor decreases, the total emissions from buildings in 2050 will be slightly higher in the most progressive retrofitting scenario, as this scenario also envisages the rapid development of photovoltaics, the production of which is exported to the grid. However, this only provides a methodology for calculating emissions from the building sector and the specific role of electricity and photovoltaics.

In the Hypothetical Scenario until 2050, the total emissions of the building sector can be reduced by up to 90% compared to 2016 due to the integration of photovoltaics and the consideration of the EF3 combination of emission factors.

4. Discussion

4.1. Uncertainties

Due to the scale of the energy model, a number of simplifications were required in this study, which inevitably lead to uncertainties.

The main source of uncertainty is the emission factors used. In contrast with the previous study from 2016 [31] published in 2019, which was based on the emission factor of electricity from the grid, which was based on the already obsolete value of 1.17 kg/kWh specified in the then valid decree for conducting energy audits, here, we used an emission factor closer to the statistical values for the Czech energy mix of 0.6 kg/kWh, which is almost half the old value. This led to a significant correction toward a reduction in the resulting CO_2 emissions. In future work, the emission factor change during the day and over the year in various situations should be considered, and the marginal emission factor should be calculated for the specific subcategories of the national building stock, including forecasting future scenarios related to the future composition of the power sector, flexibility and smartness of the energy grid, and flexibility and smartness of the buildings (as leading examples of these studies, see Kiss et al. [53] or Clauß et al. [54]).

Another source of uncertainty is that the emission factors were not used dynamically, and some back loops were not considered. For example, a reduction in the emission factors for both gas and district heating should be reflected in the reduction in the emission factor for electricity cogeneration in heating plants.

Emission factors for renewable energy sources were considered to be zero, but in reality, this is not the case. For example, to obtain heat from solar collectors, auxiliary energy is needed, which was neglected. Similarly, a zero emission factor was used for biomass, as the condition of renewable nature was assumed to be met, which means sustainable cultivation of biomass so that no more biomass is used than can be grown. However, it is uncertain whether this condition will be met in the future. Emissions related to the extraction and processing of biomass were also neglected.

Uncertainties in emission factors were partially solved by the performed sensitivity analysis for the target year 2050, which showed how the individual scenarios behave when considering the gradual reduction in emission factors.

Other sources of uncertainty are the assumptions of the future development of the share of energy sources in buildings and thus various fuels or energy carriers. The definition of their scenarios was preceded by an expert discussion and analysis of available documents. We estimated that the effect of the deviation from the assumed share of resources in buildings is less than the effect of the inaccuracy of emission factors.

Some uncertainties arise from the nature of the input data of the time evolution of final energy consumption in buildings, which was based on a simplified energy model and assumptions about the future development of the building stock.

In addition, there are uncertainties in the marginal climatic conditions. In the previous study from 2016 [31], energy consumption was modeled in two climate scenarios, RCP4.5 and RCP8.5, to determine the impact of changes in climatic conditions in the Czech Republic on the final energy consumption in buildings. With regard to the expected increase in temperatures in both climatic scenarios, the assumption of an increase in consumption for cooling and air conditioning and a decrease in consumption for heating was added to the energy model. The resulting effect was a reduction in energy consumption in individual scenarios in 2050 by 1.7% to 2.3% for RCP4.5 and 5.5% to 6.4% for RCP8.5 compared with the baseline scenario. This reduction would also affect emissions. Due to the relatively small variance in consumption and the relative laboriousness of the modeling results in this updated study, these differences were not incorporated.

Energy-efficient retrofitting of the building stock will be associated with the production of associated greenhouse gas emissions, which will be released as a result of the extraction of raw materials, the production of building materials and energy systems, their transport, and the construction processes for their incorporation. These embodied emissions have not yet been thoroughly considered as they have not been considered significant in relation to operational emissions. However, once operational emissions from buildings can be reduced to zero, the combined emissions from construction products and HVAC systems will become more important and will significantly impact the overall production of greenhouse gas emissions related to the building stock, as indicated by recent studies [29]. A good example of various material considerations in such analyses is presented in [55].

4.2. Discussion of the Results in the Context of Previous Studies

Although the previous study from 2016 presented the share of buildings in national CO_2 production as being 43%, this refined study reports a 34.7% share, which is closer to the European average of 36% reported by the European Commission [7].

The calculated reduction potential for the national building stocks' CO_2 production in 2050 ranges from 27.6% to 52.0% without considering the uptake of BIPV, and from 43.6% to 86.9% when factoring in the rapid uptake of BIPV. These figures are not comparable to the relatively low reduction potential reported from the Asian countries mentioned in the introduction, where the massive growth in building stock is expected. However, the resulting figures are compatible with the GHG saving potential ranges for 2050 from Germany (35–65%) [25–27] and with the figures presented [30] for Czechia (CZ-ENTRANZE for 2030: 40%; CZ-Mapping for 2030 37%; CZ-Briskee for 2030: 38%; CZ-Progressh for 2030: 26%). The report does not include Czech figures for 2050, but the figures for 2050 for the neighboring Slovakia are 72% (ZEBRA), 70% for Germany (ZEBRA), and 60% for Poland (ZEBRA).

4.3. Recommended Policy Actions

The CfB issued a report [40] that summarized the long-term strategy for the renovation of buildings, which aligns with the results of the investigations presented in this paper. The report (in its Section 11) summarizes the recommendations of the following measures to be taken to achieve the national climatic targets:

- Policy measures:
    - Inclusion of the modeled scenarios into the national energy policy;
    - Inclusion of the savings measures proposed in the study into sectorial policies.
- Economic measures:
    - Maintain all incomes from the EU Emission Trading Scheme dedicated for GHG emissions reduction in the existing subsidy scheme, New Green Savings Programme for energy retrofitting of residential buildings and support new construction meeting the passive energy standard and with additional financial instruments;
    - Maximize the use of the European Structural and Investment Funds and the European Commission's Modernisation Fund for increasing the energy efficiency of public and commercial buildings and the rollout of renewable energy systems for buildings;
    - Combine the investments with energy performance contracting (EPC) in the public sector;
    - Using the above-mentioned financial sources and EPC for governmental buildings, which shall be used as examples of best practices (following the EU Energy Efficiency Directive);
    - Provide financial support for energy-efficient social housing in the form of training social workers in do-it-yourself energy efficiency measures for low-income people.
- Legislative and administrative measures:
    - Tightening of the energy performance standards for subsidized building renovations. The actual standard was set as a cost optimum, but when a project is subsidized, the requirements can be shifted accordingly;
    - Improving the standard for nearly zero energy buildings (which is, in the actual Czech implementation, less demanding than passive housing standards) closer to the passive house standard equipped with renewable energy systems;
    - Harmonizing the boundary conditions and calculation methods for the Czech implementation of the Energy Performance Certificates;
    - Examining the possibility of tax benefits for energy-efficient buildings;
    - Ensuring coherent requirements of construction legislation and harmonized energy performance requirements in the building permission process;
    - Broadening the existing ENEX system for reporting and evaluation of energy savings.
- Education and counseling measures:
    - Strengthening support for consultancy by extending the existing partly subsidized Energy Consulting and Information Centers network and by presenting examples of good practices including their economic performance;
    - Preparation of targeted methods to support quality project preparation in the public sector, i.e., the creation of project stocks for investment in all building segments which needs to be further developed;
    - Increasing public awareness among real estate owners on the benefits of deep energy retrofits;
    - More intensive training and education on all scales.
- Research and development:
    - Supporting the research and development of new materials, technologies, and processes that can significantly reduce the costs of implementing energy-saving measures and local renewable energy systems. Opportunities for targeted support of science and research in the field of energy-efficient construction should be sought.

5. Conclusions

In this study, we quantified the potential for CO_2 emission reductions from the operation of the Czech building stock according to updated building retrofitting scenarios and evaluated the possible contribution of energy-saving measures applied to the building stock to national emissions commitments.

The calculations were based on the modeled final annual energy consumption of the CBS in four retrofitting scenarios in the years 2016–2050. The results showed that the building stock produced a total of 36.9 Mt CO_2 in 2016, with 23.2 Mt CO_2 originating from residential buildings and 13.7 Mt CO_2 from nonresidential buildings. The share of residential buildings in national emissions was approximately 21.8%, the share of nonresidential buildings was 12.8%, and the total share was 34.6%.

The results of the calculation showed the potential for reducing operating emissions without considering the photovoltaics of the CO_2 buildings of the Czech building stock until 2050, ranging from approximately 27.6% in the Baseline Scenario to 52.0% in the Hypothetical Scenario. When BIPV was included, this reduction ranges from 43.6% to 86.9%. Compared with 1990 emissions, the reduction range under various assumptions for building retrofitting and the development of photovoltaics is between 69% and 93%.

Assuming a balanced share of industry sectors in reducing greenhouse gas emissions, the national climate commitment for the building stock in 2050 was calculated as 11.4 Mt CO_2. The resulting values for the individual scenarios were compared with this target value.

The comparison of emission values in individual scenarios, listed in Tables 8 and 9, with the maximum target value needed to meet the national emission commitment of 11.4 Mt CO_2 showed that the commitment can only be met by implementing at least the Progressive Scenario for the retrofitting of buildings with the simultaneous development of photovoltaics. In the Hypothetical Scenario, the target would be met as early as 2040, and in 2050, emissions from the building stock would be close to the target of their full decarbonization. The Baseline Scenario led to almost double the values compared with the required target for 2050. The Governmental Scenario exceeded the target value by 56%.

Achieving truly zero emissions in the future must be heavily supported by reducing electricity, district heating, and gas emission factors, and/or significantly changing the share of buildings in energy sources so that high-emission sources are not used, and/or pairing buildings with carbon capture and storage technologies in the future.

To meet the Czech Republic's emission commitment, it is necessary to reduce the annual national production of emissions by 73.8 Mt CO_2 by 2050. In the case of the implementation of the Hypothetical Scenario with photovoltaics, the CBS would save 31.9 Mt CO_2 per year, which would contribute to a reduction at the national level by reducing emissions by a total of 43.2% compared with the 2016 emissions benchmark.

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Appendix A. English Summary of the Data from the Report on the Investigation of the Czech Residential Building Stock

This appendix summarizes the main information provided in the report Průzkum fondu rezidenčních budov v České republice a možnosti úspor v nich, which describes the energy modeling of the residential building stock [36]. In the text below, the page numbers in the report are referenced, which is available at http://sanceprobudovy.cz/wp-content/uploads/2018/04/pruzkum-rezidencnich-budov-v-cr.pdf (accessed on 21 March 2021).

The demand for energy for heating for the base year was calculated from simulated samples of residential buildings in the categories of single-family houses and multi-family houses (page 8). Both categories were broken down to subcategories by year of construction (before 1920; 1920–1945; 1946–1960; 1961–1980; 1981–1994; after 1994) and by the level of floors above ground. The categories were also broken down by the number of floors (single-family houses: 1; 2; and 3; multi-family houses between 1 and 11 per floor, then a category of buildings above 11 floors). For each category, a parametric sample of 1000 buildings describing various geometries and thermal properties of the building envelopes was created. The resulting energy demands for heating were recorded for each building and for the whole category and they were coupled with the statistical data on the Czech residential building stock. The resulting figures were compared with the statistical data on energy and fuels consumption, which served as a basis for the calibration of the model.

The related statistical data on the categories by number of units and floor areas are summarized on pages 11–13 (single family houses) and 14–16 (multi-family houses). The chart on page 17 shows the amounts of residential buildings by number of floors.

The considered U-values of the components of building envelopes per category by the year of construction are summarized on pages 18–20 (Figure 9 shows U-values of external walls; Figure 10 U-values of roofs; Figure 11 U-values of floors on the ground; Figure 12 U-values of windows and doors).

Table A1. Considered U-values for the components of building envelopes of single-family houses by the year of construction (in in W/m^{2}K) Reproduced from [36], Šance pro budovy: 2016.

Year of Construction	Before 1920		1921–1945		1946–1960		1961–1980		1981–1994		After 1994	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Roofs/floors below attics	0.66	1.05	0.83	1.48	0.68	1.48	0.64	1.01	0.26	0.55	0.17	0.42
External walls	0.83	1.31	1.02	1.62	1.02	1.70	0.90	1.66	0.38	0.59	0.19	0.30
Floors on ground	2.42	3.84	0.77	1.78	0.77	1.34	0.68	1.52	0.38	1.31	0.34	0.62
Windows and doors	1.80	2.85	1.80	2.85	1.80	3.44	2.03	3.21	1.50	2.90	0.83	1.54

Table A2. Considered U-values for the components of building envelopes of multi-family houses by the year of construction (in in W/m^{2}K) according to [36].

Year of Construction	Before 1920		1921–1945		1946–1960		1961–1980		1981–1994		After 1994	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Roofs/floors below attics	1.10	3.09	0.60	1.78	0.76	1.72	0.43	1.01	0.35	0.55	0.24	0.38
External walls	0.83	1.62	0.83	1.31	1.07	1.70	0.70	1.43	0.55	0.90	0.19	0.59
Floors on ground	0.49	0.77	0.77	1.22	0.76	1.22	0.69	1.09	0.62	1.31	0.30	0.53
Windows and doors	1.80	2.85	1.80	2.85	2.18	3.44	1.83	3.21	2.03	3.44	1.20	1.90

Pages 21–23 report on the geometric characteristics of the family houses and Table 13 on page 23 shows in detail used geometric characteristics for the group of single-family houses with two floors.

On pages 24–25, datasets obtained from the Ministry of Industry and Trade of the Czech Republic on the total energy consumptions for space heating, domestic hot water preparation and for lighting in 2011 are presented.

Pages 25–27 present an estimation of a share of buildings with applied thermal insulation. It is based on the study from the previous project PanelSCAN and on the estimation of the amount of installed external thermal insulation composite systems based on sales statistics by the Czech Guild for Thermal Insulation of Buildings. The resulting estimation of already insulated buildings used in the calculations is 35%.

Considered efficiencies by energy sources are shown in Table 20 on page 28, which shows calculated energy demand for heating and considered efficiency by type of fuel. The considered combined energy efficiencies for heat sources were:

- Oil and petroleum products: 81.6%;
- Natural gas: 81.6%;
- Coal and coal products: 72.0%;
- Biomass: 72.0%;
- Heat from district heating systems: 94.1%;
- Electricity: 85.5%;
- Heat from solar systems or from heat pumps: 96.0%.

Assumed consumptions of the hot water are shown in Table 24 on page 31 (in single-family houses 35–55 L per person and day, in multifamily houses 12.78–20.08 L per person and day). The considered volumes of the hot water storages and the lengths of the heat distribution piping are in Annex 3.

Table 34 on page 36 presents the calculation of the energy consumptions for lighting.

From page 38 on, the report discusses the investment costs; the economic aspect is out of the focus of this paper, so it is skipped in this description.

Appendix 1 on pages 60–64 summarizes the geometric characteristics, proportions of the building envelopes' components, mean U-values of the building envelopes and the percentage of glazed areas for all categories of the single-family houses.

Appendix 2 on pages 65–72 provides a summary of the energy simulation results. The energy consumption for the baseline year for the single-family houses is shown in Table 59 on page 66 and for the multifamily residential houses in Table 64 on page 71.

Appendix B. English Summary of the Data from the Report on the Investigation of the Czech Nonresidential Building Stock

This appendix summarizes the main information provided in the report Průzkum fondu nerezidenčních budov v České republice a možností úspor v nich, aktualizovaná verze prosinec 2016, which describes the energy modeling of the nonresidential building stock [37]. In the text below, the page numbers in the report are referenced, which is available at http://sanceprobudovy.cz/wp-content/uploads/2018/04/pruzkum-nerezidencnich-budov-v-cr.pdf (accessed on 21 March 2021).

The energy modeling of the nonresidential building stock was based on two samples of buildings. One is a sample of 100 buildings for which an energy model is available to assess the energy performance certificate. The model is created for all buildings in the same way and in accordance with Decree 78/2013, Coll., TNI 730331, and EN ISO 13790. Furthermore, the study evaluates a sample of 20 buildings for which, in addition to the energy model, real energy consumption (especially for heating) based on energy bills is also available. The text then compares the calculated values according to standard energy certificate calculation method and the real consumption of buildings. The calibration of the energy model was made by comparison of the simulated energy consumption with the real energy consumption on twenty existing buildings. Based on these comparisons, a correction formula for their extrapolation on the whole nonresidential building stock was derived. It was based on a sensitivity analysis that identified the key parameters: surface area/volume ratio, ratio between the mean U-value and the reference U-value used in the declaratory energy performance calculation method, mean indoor temperature and the overall efficiency of the heating system.

The report starts with the introduction of the sample of 100 buildings. The building typologies included in the study were office and administrative buildings, commercial buildings, educational buildings, cultural buildings, hotels, restaurants, medical facilities, sports facilities, storage buildings, and those with mixed use. Appendix 1 on pages 69–80 presents photos of all buildings for illustration. The buildings' heated floor area varied from 163 m^2 and 32,211 m^2; the mean area was 4502 m^2 and median 2313 m^2 (details on distribution chart (Figure 2), volumes (Figure 3), A/V ratios (Figure 4) and glazing ratios (Figure 5) are on pages 6–7). Section 2.2 on pages 9–11 describes the U-values and boundary conditions in the considered scenarios, which are summarized in Table 1 of this paper above.

Section 2.3 presents results of the simulations. Figure 6 shows the distribution of mean U-values of the modeled building's envelopes and Table 8 presents the energy classifications of the building envelopes by scenario. Table 9 shows the calculated energy demands for heating; for the baseline scenario, the results span between 40 and 371 kWh/m^2. The mean value of energy demand for heating is 135 kWh/m^2, which results in 233 kWh/m^2 in final energy consumption after figuring in the auxiliary energy consumption and the system efficiencies.

Section 3 works with the sample of real twenty buildings with data from energy audits and elaborates on the energy savings potential in scenarios.

Section 3.2 documents the design of the correction factor formula by using the sensitivity analyses, and the formula itself is presented on page 29.

Section 4 presents the outcomes of the application of the correction formula on the sample of 100 buildings, which shifts the span of results in the final energy consumption to the range of 40–256 kWh/m^2 and the mean value to 108 kWh/m^2. Section 4.2 describes the economic evaluation of the energy retrofitting measures (which is out of the scope of this paper).

Section 5 summarizes the background statistical data that were used for the energy modeling of the Czech nonresidential building stock. General data are presented on pages 38–46, page 47 provides granular information on educational buildings.

Section 6 deals with the procedure of the extrapolation of economic considerations to the whole nonresidential building stock.

Section 7 provides a detailed description of the modeled heat sources and their parameters. The dimensioning of the modeled heat sources was performed for the extreme external temperature -15 °C (which is more or less representative for Czechia on average) and safety surcharges of 20% were added. As shown in Table 39, the power of the heat sources varied from 20 kW to 3 MW, the average power was 330 kW for the baseline scenario. For the calculations, the heat loss calculation has been made per square meter, as shown in Table 40. Considered efficiencies of heat sources by energy type or fuel are presented in Table 43 on page 54. The prevailing heat sources and their considered efficiencies were:

- Heat from district heating systems: efficiency 98–99%;
- Natural gas: efficiency 77–98%;
- Electricity: efficiency 93–99%.

Table 60 on page 67 summarizes the energy consumption other than for heating. The largest average value of supplied energy was for the lighting (15 kWh/m^2a) and for hot water preparation (14 kWh/m^2a). For cooling, the average value of 1.3 kWh/m^2a was stated, but it should be noted that only 33% of the buildings had cooling. The average value for buildings where cooling occurred was 4 kWh/m^2a. It should also be noted that even for buildings that have energy supplied for cooling, these are usually only some parts of the buildings that are cooled. From the point of view of the methodology of the calculation of supplied energy, cooling is approached differently from heating and the supplied energy is identical to energy consumption. The specific energy demand for cooling would therefore be approximately 12 to 16 kWh/m^{2}a for buildings with cooling, taking into account a cooling factor of 3 to 4. At the same time, however, it should be noted that the calculation of cooling energy consumption using the monthly method ČSN EN ISO 13790 shows irrelevant results in many cases.

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SYNTHESIS

Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions

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Abstract

Target values for creating carbon budgets for buildings are important for developing climate-neutral building stocks. A lack of clarity currently exists for defining carbon budgets for buildings and what constitutes a unit of assessment—particularly the distinction between production- and consumption-based accounting. These different perspectives on the system and the function that is assessed hinder a clear and commonly agreed definition of 'carbon budgets' for building construction and operation. This paper explores the processes for establishing a carbon budget for residential and non-residential buildings. A detailed review of current approaches to budget allocation is presented. The temporal and spatial scales of evaluation are considered as well as the distribution rules for sharing the budget between parties or activities. This analysis highlights the crucial need to define the temporal scale, the roles of buildings as physical artefacts and their economic activities. A framework is proposed to accommodate these different perspectives and spatio-temporal scales towards harmonised and comparable cross-sectoral budget definitions.

Policy relevance

The potential to develop, implement and monitor greenhouse gas-related policies and strategies for buildings will depend on the provision of clear targets. Based on global limits, a carbon budget can establish system boundaries and scalable targets. An operational framework is presented that clarifies greenhouse gas targets for buildings in the different parts of the world that is adaptable to the context and circumstances of a particular place. A carbon budget can enable national regulators to set feasible and legally binding requirements. This will assist the many different stakeholders responsible for decisions on buildings to coordinate and incorporate their specific responsibility at one specific level or scale of activity to ensure overall compliance. Therefore, determining a task specific carbon budget requires an appropriate management of the global carbon budget to ensure that specific budgets overlap, but that the sum of them is equal to the available global budget without double-counting.

Keywords: building stock; buildings; built environment; carbon budget; climate policy; greenhouse gases (GHGs); mitigation

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1. Introduction

The climate crisis is prompting an intensive examination into the reduction of anthropogenic greenhouse gas (GHG) emissions. The relevance and pressing nature of this topic is highlighted by the integration of climate change mitigation measures into the globally recognised Sustainable Development Goals (SDGs) (UN 2015), through SDG 13: 'Take urgent action to combat climate change and its impacts'. The alarming reports of the Intergovernmental Panel on Climate Change (IPCC) (2018a: 32) and the commitments to national GHG emission-reduction measures within the framework of the United Nations Climate Change Conference of the Parties (COP) (UN 2019) have brought this topic to the top of the political agenda.

In the meantime, urbanisation is expected to add 2.5 billion people to the global urban population by 2050 (Swilling *et al.* 2018). Together with the pressure to overcome the already sizable housing deficit and lack of decent built environment, this urbanisation peak will increase the construction material requirements and GHG emissions associated to their production (Göswein *et al.* 2018). Recent studies show the small amount of progress achieved in reducing GHG emissions associated with construction of new buildings (Röck *et al.* 2020). Furthermore, in countries where most of the building stock has been built, fast and deep energy retrofit is needed of the residential building stock. The IPCC states retrofit rate of the residential building stock should increase from today's 1–2% per year up to 5% per year (in Organisation for Economic Co-operation and Development (OECD) countries) (IPCC 2018b). This renovation activity also contributes to GHG emissions through the production of insulation materials (Heeren & Hellweg 2018). Recent studies by the International Energy Agency (IEA) estimate that cement and steel used for construction and renovation of buildings would be responsible for an average of 2.3 Gt CO_2e (CO_2-equivalent) emissions annually up to 2060. An ambitious policy on material reduction demand could curb these emissions by more than 50% (IEA 2019). A current estimate of embodied GHG-emissions from buildings is 10 Gt CO_2e/yr. This amount could be reduced to only 2 Gt with decisive actions or reach 16 Gt CO_2e/yr if current trend is continued (Global Alliance for Buildings and Construction 2016). Buildings could even act as a carbon sink if insulation materials (Pittau *et al.* 2019) or structural materials (Churkina *et al.* 2020) are not based on fossil fuels but switched to bio-based materials.

Buildings are clearly identified by policy-makers as a key point to reduce GHG emissions (Anderson, Wulfhorst, & Lang 2015). However, the different stakeholders such as portfolio managers, national political leaders, heads of industry, civil and building engineers, and designers do not include the same activities under the topic called 'buildings'. Sometimes only the emissions related with the use of buildings are included (*e.g.* C40cities strategies; De Blasio 2017). Sometimes emissions related to cement and steel production are targeted (*e.g.* European Trading Scheme—ETS), but this will include building construction along with other activities such as infrastructure or automobile production.[1] Sometimes, the production of goods related to construction and operation of buildings within the country are included but not the imports are excluded, *e.g.* UK carbon roadmap (Miliband 2008). Sometimes the level of action is at the city level and budget is constrained by the population living inside administrative boundaries (Mirabella & Allacker 2020). This creates confusion as it is difficult to grasp the boundaries of what is considered. The prevailing confusion becomes an obstacle, because actors do not have a complete picture of the field of action corresponding to their perspective and their tasks. Therefore, a clear system of objectives, actors, fields of action and possibilities of influence is needed. The goal of reducing GHG emissions assigned to the built environment must be translated in such a way that each group of actors can develop strategies for their specific area of work and responsibility in order to measure the success of their activities.

The objective of this paper is to define an operational framework to clarify the targets for climate mitigation in the built environment in the different parts of the world. This operational framework needs to be transparent, by reporting hypotheses and assumptions made. It also needs to be consistent across scales and stakeholder's task in order to avoid double counting or gaps in carbon accounting. It responds to a practical need for policy-makers, regulators and administrators, designers and clients to have a clear target value for GHG emissions per m^2 or per m^2.yr. Such a design target might be different depending on the local climate and social needs.

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2. The carbon budget approach

The focus of this paper is on the definition, allocation and interpretation of a carbon budget approach. The advantage of this approach is that many actors in the construction sector already adhere to other defined budgets that must not be exceeded. A carbon budget can be adapted to the respective object under consideration and its system boundaries by choosing suitable reference values. It is thus an important instrument for reducing undesirable effects on the global climate.

The carbon budget refers to the maximum cumulative amount of anthropogenic GHGs which can be released in the atmosphere in order to keep the global Earth temperature within a given limit (IPCC 2018b). Transgressing this budget raises the risk of disturbing the climate system beyond an irreversible tipping point (Steffen *et al.* 2018). Climate change caused by GHG emissions is perhaps the most pressing environmental issue.

2.1. A global carbon budget

The IPCC has investigated different scenarios for global warming and related 'emission reduction pathways' (IPCC 2014). Based on this scientific evidence, policy-makers have agreed to use 2°C target as important objective for international climate policy (UNFCCC 2016), even though a 1.5°C target is now under consideration (IPCC 2018a: 32).

However, higher GHG concentration levels than those consistent with long-term temperature targets may be possible if negative emissions technologies reabsorb this concentration excess before 2100 (van Vuuren *et al.* 2013). Such (limited) overshoot scenarios can be attractive as they require less short-term reductions and seem to have only limited additional risks except that it shifts the efforts towards the next generation to implement these uncertain and costly carbon capture and storage technologies (Van Vuuren *et al.* 2017). A synthesis of these different carbon budgets depending on the target, 2 or 1.5°C and the potential use of negative emissions by the end of the century is presented in **Table 1**.

2.2. Allocation issues: per countries and capita

Once a global GHG budget has been defined, it can be allocated to specific actors: a national government, a city government or even a single person; or their respective area of activities. This step requires the carbon budget concept to be used as a tool in guiding practical decisions and actions of specific stakeholders.

The disaggregation of the global budget into ones for particular stakeholders (or area of activities) involves two dimensions: specification of the level of disaggregation (country to person) and of the accounting principle that determines how much of it is used up by particular activities. A common first *level of disaggregation* is by countries, within which the budget could be broken down further by, *e.g.*, economic sectors, areas of need or per capita.

In the literature, allocation mechanisms are discussed mainly for disaggregation at the country level (Alcaraz *et al.* 2019). The smaller the budget assigned to a country in relation to current emissions, the more mitigation effort is implied for that country. The allocation of budgets thus often is framed under the perspective of effort-sharing. Allocation mechanisms have been categorised based on the three equity principles of responsibility, capability and equality, and on their various combinations, as specified in IPCC AR5 (Clarke *et al.* 2014):

- *Responsibility:* Refers to whether historical emissions are considered. If so, their over-proportional occurrence reduces the share of a country in the global budget that is still remaining as of today.
- *Capability:* Draws on the UNFCCC principle that countries should act 'in accordance with their common but differentiated responsibilities and respective capabilities and their social and economic conditions' (UN 1992, Article 3). In budget allocation this implies a larger budget share for countries ranking lower in indicators such as gross domestic product (GDP) or the human development index (HDI).
- *Equality:* Often means 'allocations based on immediate or converging per capita emissions' (Clarke *et al.* 2014: 458). Immediate equality in per capita terms apportions the remaining global budget to countries based on their population. Equality that converges at a future point in time (possibly as late as 2050) involves a type of 'grandfathering' which acknowledges that current high emitters need time to make a transition. However, this attributes legitimacy to the status quo of highly unequal levels of emissions and even justifies their further persistence. This approach ensures highly industrialised countries have far more emission rights in the transition period, but no justification is provided for *preserving* this inequality beyond the fact that countries happen to have reached highly unequal levels (Williges *et al.* 2020).

Table 1: Total remaining global carbon budget expressed in Gt CO_2e: It includes all greenhouse gas (GHG) emissions.

	Without negative emissions			**With negative emissions**		
	T1.5C	**WB2C**	**LB2C**	**T1.5C**	**WB2C**	**LB2C**
2020–50 (Gt CO_2e)	500	700	1100	1700	1900	2300
2050–2100 (Gt CO_2e)	Net zero	Net zero	Net zero	–1200	–1200	–1200

Note: A scenario likely below 2°C (LB2C) is in line with the IPCC's 5th Assessment Report, as cited in Rogelj *et al.* (2016) with 50% below 2°C. A well below 2°C scenario (WB2C) is based on Rockström *et al.* (2017) with more than 66% below 2°C. Finally, a target of 1.5°C (T1.5C) is defined according to Millar *et al.* (2017) with 50% below 1.5°C.

Source: Adapted from Williges *et al.* (2020).

These three equity principles have also been applied in various combinations, as specified in **Table 2**.

The issue of national budgets is not pursued further in this paper. However, it is assumed that a national carbon budget defined in accordance with the approaches listed in **Table 2** is the starting point for a further subdivision into sectors, fields of action and areas of need.

2.3. Defining specific budgets according to the object of assessment

2.3.1. Mediating production and consumption models

The implementation of carbon budgets should be applicable on multiple levels, across activities. **Figure 1** illustrates a supply–demand concept. From a built environment perspective (buildings and infrastructure), the supply or production side can be represented, for instance, by the different industry sectors, which provide goods and services as an input. On the demand or consumption side one can find people and their different areas of need.

A production-based accounting approach would consider only direct emissions at the construction site (*i.e.* the *in situ* emissions from construction vehicles and equipment using fossil fuels). It is useful for the producers, yet tends to ignore the influence that the agents of final demand have on emissions during earlier steps in the production value chain. Alternatively, the emissions that had occurred in the production of upstream processes including emissions

Table 2: Categorisation of budget allocation approaches.

IPCC category	Description
Responsibility	Use of historical emissions to derive future reduction goals
Capability	Approaches relating goals to gross domestic product (GDP) or human the development index (HDI), other basic-needs-fulfilling approaches
Equality	Allocation based on immediate or converging emissions per person
Responsibility, capability and need	Includes approaches placing an emphasis on historical responsibility, balanced with capability and the need for sustainable development
Equal cumulative per capita	Combines equality with responsibility (cumulative accounting for historical emissions)
Staged approaches	Differentiated commitments, various stages, sectoral approaches or grandfathering approaches

Sources: Based on Höhne, den Elzen, & Escalante (2014) and Williges *et al.* (2020).

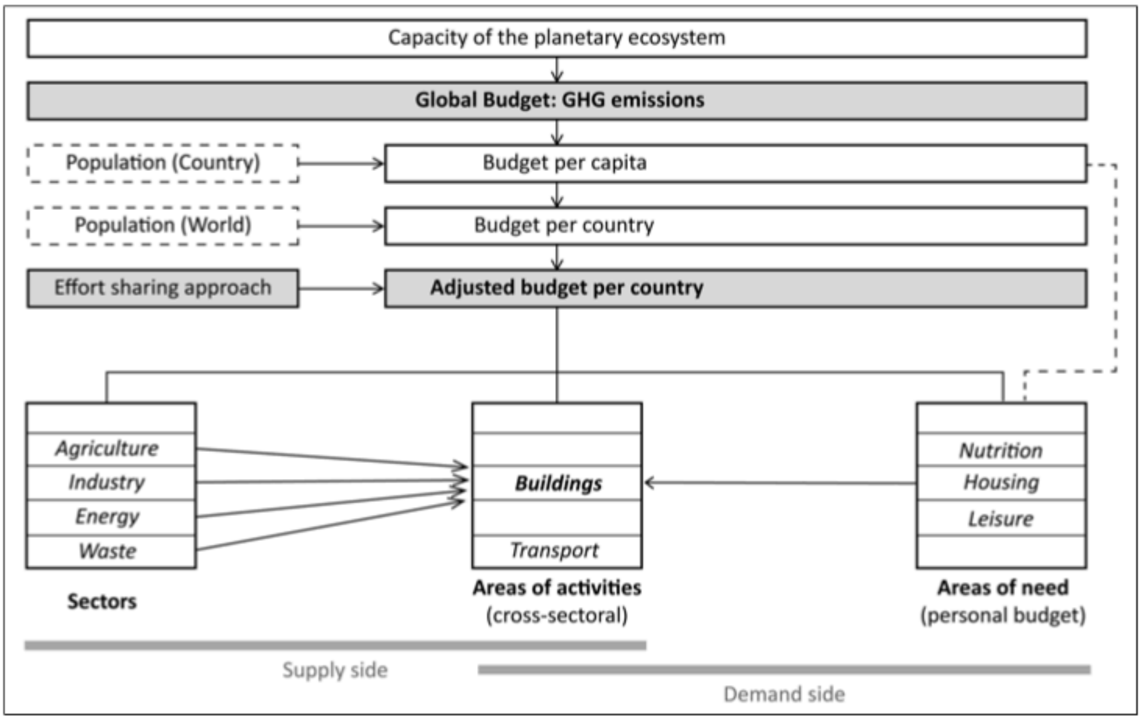

Figure 1: Different points of view for defining budgets across activities. The industry sector includes the construction product industry, construction industry and real estate industry. The agriculture sector includes by-products used as bio-based building materials.

from the production of materials or infrastructure required to provide the final product can be considered. This latter approach follows a consumption-based accounting principle. However, including this consumption-based accounting approach might not fully address the relevance of production decisions for products that are 'exported' to other agents for their final demand. Ultimately both accounting principles should be acknowledged (Steininger *et al.* 2016), such that agents' decisions are based on an indicator system suitable for their needs that avoids pathways with unintended counterproductive implications for the global GHG concentration.

2.3.2. Sectoral approach

The definition of economic sectors can follow different approaches, *e.g.* the classical three-sector model of primary, secondary and tertiary sectors, or an owner-based approach distinguishing public and private sectors, amongst others. Several international and national standards have been established for the classification of economic sectors for statistical purposes, such as, *e.g.* the International Standard Industrial Classification of All Economic Activities (ISIC) for worldwide use developed by the United Nations Statistics Division (UNSD) (2008), or the Statistical Classification of Economic Activities (NACE) classification of economic activities for the European Union (Eurostat 2008) as well as a multitude of national classifications that, more or less, align with these international systems. In practice, several definitions and conventions are used depending on the context these are defined in. For instance, the IPCC's *1.5°C Special Report* applies a sectoral perspective based on 'energy end-use sectors' focusing on society's main sectors, and includes buildings, industry, transport, energy, and agriculture, forestry and other land use (AFOLU) (IPCC 2018b). The current authors prefer an approach which, from a macro-economic point of view, divides the national economy into basic sectors such as agriculture, industry, energy and waste management. The industry sector is further subdivided and includes the construction product industry, construction industry and real estate industry.

A common strategy for implementing emission reductions across sectors and activities, *e.g.* in policy roadmaps, is to follow a contraction and convergence approach. This means defining emission reduction targets for individual sectors based on current (or past) levels of GHG emissions, *e.g.* a 50% reduction in GHG emissions by 2030 from a 1990 baseline.

2.3.3. Areas of activities

Based on the GHG protocol (WRI & WBCSD 2013), the GHG emissions can be defined for the national building stock or one residential building:

- *Direct emissions (scope 1)* from building operation, *e.g.* GHG emissions from burning fossil fuels for heating and cooling, lighting, hot water, *etc.*
- *Upstream emissions (scope 2)* from provision of operational energy from the respective energy sources, *e.g.* indirect emissions of district heating or electricity.
- *Indirect emissions (scope 3)* related with upstream and downstream activities, including the production and processing of building materials as well as construction, maintenance and replacement, renovation and demolition of the building at the end of its service life.

All these different perspectives—scopes 1–3—need to be considered when assessing the emissions across the full life-cycle of 'buildings' or construction assets.

An approach is proposed here to encompass the full life-cycle of 'buildings'.

The term 'sector' is used here to refer to 'economic sectors' or its parts (*e.g.* construction product industry, construction industry, real estate industry). The term 'area of activities' is used where different industrial sectors contribute to a cross-sectoral activity, such as the 'production, construction, use and end-of-life of buildings', in short, 'buildings'.

2.3.4. Areas of need

Apportioning the global (or country) budget using a consumption-perspective (Beylot *et al.* 2019; Cabernard, Pfister, & Hellweg 2019) brings the issue of appropriate needs into focus (*e.g.* mobility, housing/shelter, nutrition; Creutzig *et al.* 2018). People's needs and practices are what creates demand, which induces economic activity and causes the associated environmental burdens (**Figure 1**). However, the imposition of carbon mitigation efforts equally across all areas of needs is socially unjust as certain needs are more fundamental (*e.g.* sufficient nutrition) than others (*e.g.* air travel) (Otto *et al.* 2019).

An important distinction must be made between essential (or basic) and advanced (or luxury) needs (O'Neill *et al.* 2018; Rao & Min 2018; Raworth 2017). For example in the area of housing, the essential need may be defined as a certain floor space per inhabitant with a decent comfort level (Rao & Min 2018). Fulfilling the basic needs for a prospective world population (approximately 10 billion in 2050) with the technology available during the transition period, will consume a certain fraction of the remaining carbon budget and can be seen as the emissions necessary to ensure the social foundation (Rao & Baer 2012). Giving priority to achieve a decent life for all—in line with the internationally agreed SDGs (UN 2015)—necessitates and justifies to increase the allocation of the remaining carbon budget to areas of basic needs (**Figure 1**). Whatever is left may then be shared among advanced needs. In the example of housing, every additional m^2 or increased comfort receives a smaller carbon budget, *i.e.* assigned an increased mitigation effort.

3. Multiple perspectives on buildings and building-related activities

It is possible to identify three largely different objects of assessment as described in **Figure 1**: the economic sectors, the area of activities 'buildings' and the area of need 'housing'. Residential buildings are a subgroup of buildings here. If constructed assets or infrastructure are included, the area of activities then become 'creation and operation of construction works' in a wider sense.

Once a clear definition of the object of assessment is given, the principles described in the previous section for dimensioning and allocating budgets can be applied to buildings as area of activities.

The economic sectors contributing to the construction, maintenance and operation of buildings are related to macroeconomic sectors such as:

- *Industry:* the production of building materials (construction product industry including upstream processes), the construction of buildings and infrastructure (construction industry), and the management of buildings and building stocks (real estate industry and facilities management).
- *Energy and water supply:* all services related to the operation of buildings and associated construction and maintenance of these infrastructure and upstream processes.
- *Waste management:* the solid and liquid waste generated during the construction of the buildings and their use.

The area of activity 'buildings' focus on the production, construction and use of the physical objects, including end of life processes (reuse, recycling and/or disposal). This area of activity focuses on different spatial boundaries, from national level to the single-building scale. In relation to such physical objects the term 'building stock' is also used.

The area of needs 'housing' relates to the area of activity 'residential buildings' which is on the demand side (Jenny, Grütter, & Ott 2014; Rao & Min 2018).

In this paper, a diversity of the objects of assessment is accepted due to the diversity of stakeholders associated with building's activities. Each stakeholder has a specific interest because each of them is responsible for the management of one specific task at one specific level/scale of activity. Therefore, determining a task specific carbon budget requires an appropriate management of the global carbon budget to ensure that specific budgets overlap but that the sum of them is equal to the available global budget without double counting.

Table 3 shows the link between the list of stakeholders involved in buildings' activities and the previously described object of assessment. The general distribution of interest for the different stakeholders is defined based on expert advice[2] and is not a result of surveys (Lin *et al.* 2017) or semi-structured interviews (Li *et al.* 2018). But there is a general agreement between the common viewpoint in this paper and other studies on the powers, interests and responsibilities of stakeholders along the value chain of building construction and use (Li *et al.* 2018; Lin *et al.* 2017; Tengan & Aigbavboa 2017; Yang, Zou, & Wang 2016).

It is clear that national and regional governments have a significant power to set rules and targets. Sustainability assessment and certification bodies, which mainly operate at the building scale and sometimes at district level (Cole 2005; Pati, Park, & Augenbroe 2006) have an influence that cannot be neglected. Actually, even if the proportion of certified buildings and neighbourhoods is low in relation to all construction activities, these organisations have been and are still pioneers in the introduction of GHG emissions target values. For instance, in Germany, sustainability assessment systems like BNB and DGNB evaluates GHG emissions during the life-cycle and set limit and target values for buildings since more than 10 years (BMUB 2014).

Households and architects mostly focus on one single building and as individual actors, their influence is hardly measurable. However, as a complete group of actors, they are the key target group for the specification of carbon budget for embodied and operational part of individual buildings as they are the one who will ultimately implement such specifications. The overall concept of a carbon budget approach is not considered at the individual level. Instead, it is either through professional organisation of architects and engineers or real estate companies which can establish rules of good practice and standards (*e.g.* SIA 2040:2017; SIA 2017) or through financials constraints and incentives which can drive individual owner's choices.

In that sense, institutional investors, property and housing companies, property funds, banks and insurance companies can decide to green their investment portfolio in relation to the carbon footprint of the buildings they own (in their role as investor and portfolio manager) or finance (in their role as financer or insurer) (TEG 2019). Financial organisations can drastically transform the construction market if clear carbon data and budgets exist for specific objects. Responsible banking could finance carbon budget compatible activities (for material producers, for real estate companies or for individual owners) in the same way as insurance companies have integrated climate change risks into their portfolio management (Dlugolecki 2000). Weber & Kholdova (2017: 6) state:

> the financial industry should develop indicators that can be used internally to measure and evaluate climate change-related performance. [...] Methods such as carbon footprinting, avoided emissions and green–brown metrics—though still in their infancy—are helpful for managing carbon-related risks and allocating climate change responsibilities.

Table 3: Mapping for type of budget versus kind of actor.

	Type of actor	**National government regulator/ assessor**	**National government administrator**	**Regional government regulator/ assessor**	**Regional government administrator**	**Building owner (all types)**	**Building operator (all types)**	**Industry: production (energy and products)**	**Building association (architecture and engineering; construction products association)**	**Architect**	**Bank**	**Sustainability certification body**	**Household**
Object of assessment													
A	**Economic sector**												
A1	Construction product industry	×						×	×		×		
A2	Energy sector (energy provider)		×					×			×		
A3	Waste management sector	×		×									
A3	Real estate sector					×					×		
B1	**Area of activity: operation**												
B11	National building stock		×					×	×				
B12	City/district				×								
B13	Building portfolio						×				×		
B14	Single building	×		×		×				×		×	×

(Contd.)

	Type of actor	National government regulator/ assessor	National government administrator	Regional government regulator/ assessor	Regional government administrator	Building owner (all types)	Building operator (all types)	Industry: production (energy and products)	Building association (architecture and engineering; construction products association)	Architect	Bank	Sustainability certification body	Household
B2	**Area of activity: full life cycle**												
B21	National building stock		×				×	×	×				
B22	City/district				×	×			×				
B23	Building portfolio		×				×		×		×		
B24	Single building	×		×		×				×	×	×	
C	**Area of need**												
C1	Housing (part: operation)	×	×			×	×			×			×
C2	Housing (part: full life cycle)	×	×			×							

4. A scale specific budget approach for stakeholders

4.1. A framework spanning spatial and temporal scales

Figure 2 illustrates the overlapping interests and the need for scale specific budgets. This provides a coherent alignment across scales. In this way, one can begin to reconcile a budget for yearly emissions of an economic sector (*e.g.* the part of the construction or the energy sector required for residential activities) with a budget for one building object over its full life-cycle. A pool of buildings such as a district, a real estate portfolio or a national building stock can also be analysed and provided with specific budgets, tailored to the respective use case. This budget can consider the current state of the building stock and/or its future evolution. Finally depending on the stakeholders' interests, one would define a budget only for emissions related with operation of these objects (building/district/portfolio/national building stock) (scopes 1 and 2), or include emissions related with their production, construction, maintenance and demolition (scope 3).

Figure 3 explicitly shows the different steps for carbon budget definition. This transparency provides a comprehensible definition of the system boundaries and the hypothesis associated with a given budget. The decision choice depends on the stakeholder's viewpoint and allows for different configurations. Key aspects to consider are:

- *Global budget:* What is the global carbon budget available? This depends on the climate model taken as well as the chosen target (1.5–2°C, *etc.*).
- *Effort sharing and allocation principles*: How is this budget shared between people, countries and industrial sectors? Which rules are applied, *e.g.* contraction and convergence, equal budget per capita, *etc*?
- *Object of assessment:* What is the object of assessment: the construction industry, building operation, one specific building, one district or a complete building stock of a defined region? Which life-cycle stages are covered and how is the budget shared across them?
- *Building budget:* is the allocated budget translated to a specific building intervention? This final step establishes a correlation between the budgets defined in previous steps and translates them to a budget per m² building floor area. This allows engineers and architects to use this budget in the design process. Furthermore, city planners or policy-makers can use such budgets to analyse and plan interventions at building stock level, such as retrofit scenarios or science-based governance of new construction allowances.

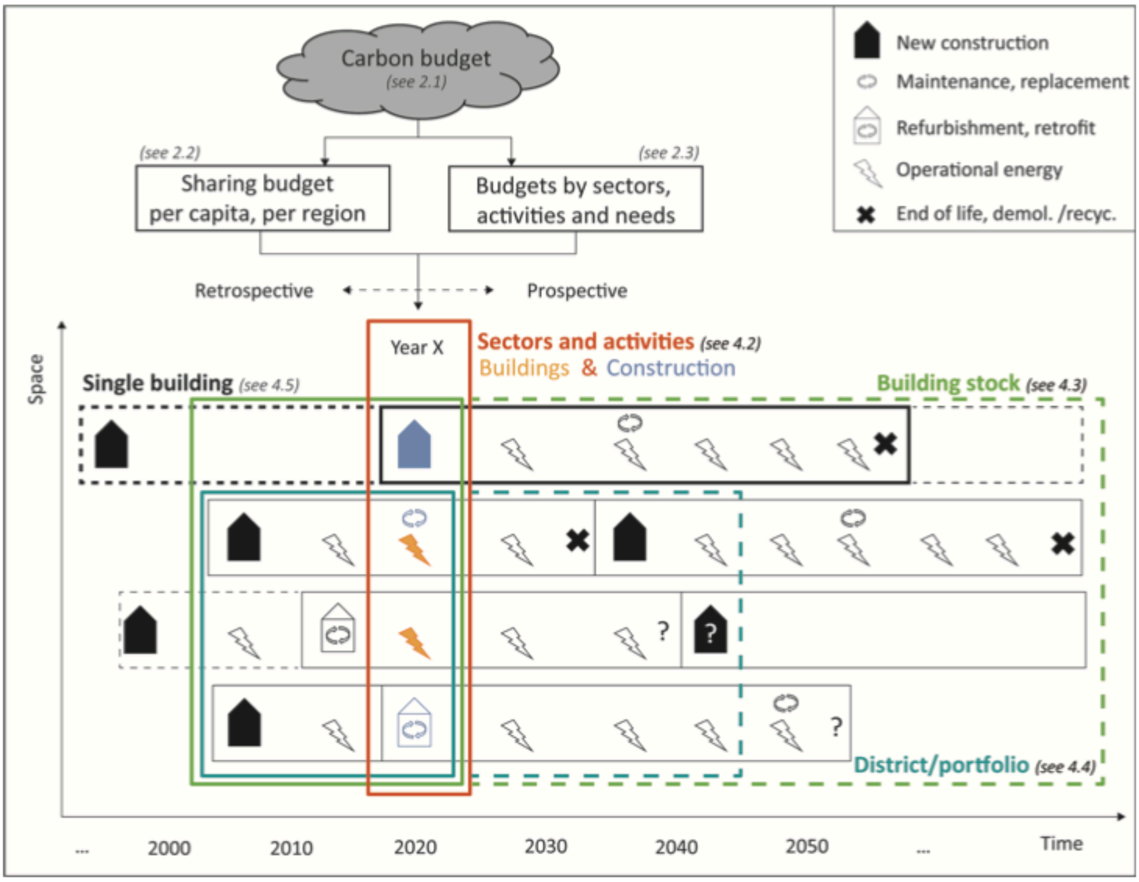

Figure 2: Four perspectives on 'buildings' and related spatial and temporal scales.

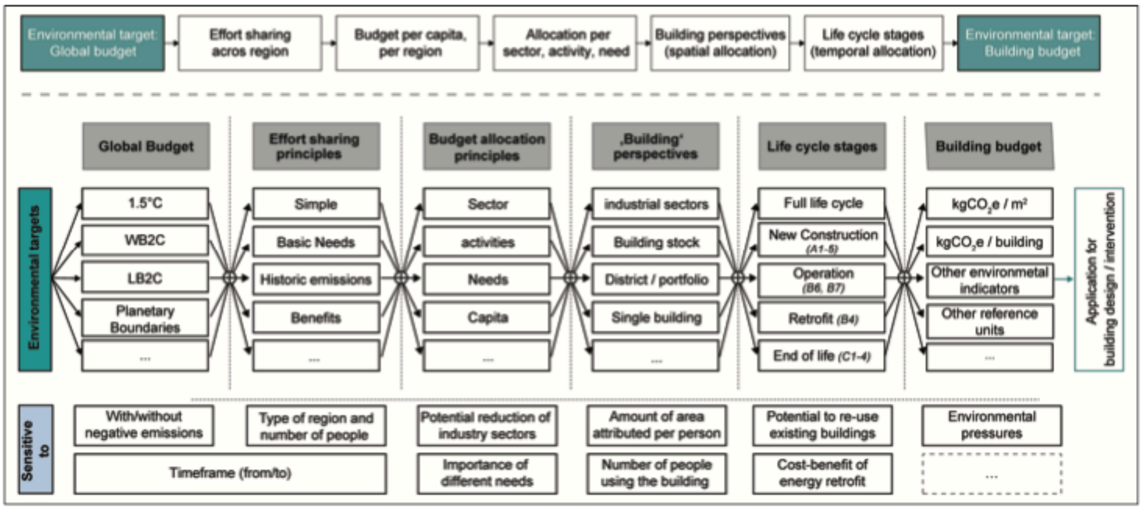

Figure 3: Decision tree for budget definition, showing the various steps and decisions to be taken and specified for definition of environmental budgets. Several aspects in this definition are sensitive to country specific characteristics (*e.g.* number of people, historic emissions, *etc.*) as well as sensitive to behavioural aspects (*e.g.* number of people using a building and area per person).

4.2. Budgets for economic sectors and areas of activities

This section provides some examples that have been promoted in different countries or regions to illustrate the different strategies and choices in defining environmental targets.

To deliver on the EU's commitment in the Paris Agreement and to respond to the objective of limiting global warming to 1.5°C, the European Commission (EC) communicated the target for GHG emissions reductions of 91–94% below 1990 levels by 2050 (EC 2018). The underlying in-depth analysis (EC 2018) presents multiple scenario-based pathways for reducing GHG emissions towards the aspired 'net-zero' levels by and beyond 2050. All scenarios rely on the implementation of CO_2 removal technologies.

Once this global EU budget calculated, it is possible to construct a yearly per capita budget considering current population as well as its evolution to 2050 (**Table 4**). Finally, the EC has also defined different strategies depending on the economic sectors considering the economic and technical feasibility of their decarbonation potentials. From a more technical point of view and following an efficiency and consistency strategy, greening the energy sector is the easiest, followed by the reduction in energy demand during building use (due to deep retrofit) and finally the decarbonation of building material production (included in industry sector) (Davis *et al.* 2018). There could also be a sufficiency strategy to reduce energy demand by a change in the occupants behaviour through the selection of appropriate comfort level and the optimisation of space demand. However, this approach is less promoted by the EC.

In the EU's long-term strategy for reducing GHG emissions, energy-efficiency measures, including the energy efficiency of building operation, play a central role in reaching 'net-zero GHG emissions by 2050' through the reduction of energy consumption 'by as much as half' compared with 2005 (EC 2018). To improve the energy performance of buildings, the EU has implemented the Energy Performance of Buildings Directive (EPBD) (EC 2010). EPBD targets are set per country and have thus so far focused on energy efficiency and, at least not explicitly, the reduction of GHG emission. Benchmarks are currently specified for the energy consumption per m² and the percentage share of renewable energy as well as minimum requirements regarding the thermal transmittance (*U*-value) of the building. While these requirements will have a substantial effect on the energy-related GHG emissions, they do not yet fully connect to the GHG reduction targets set by the EU.

Different approaches for definition of a carbon budget for the area of activities 'buildings' are also possible at the national level. For instance, the German Climate Protection Plan 2050 (BMUB 2016) mentions 'buildings' as an area of action. It represents the emissions related with the energy used for the operation of buildings. There is a specific objective for 2030 and it can be interpreted as a partial carbon budget for building operation emissions. For 2050 the target is a climate-neutral national building stock—when considering the operational part. There is no target or budget in place for the embodied part at the moment (**Table 5**).

The embodied emissions related to building activities are considered in the area of action 'industry', which includes construction product industry among others. Depending on the feasibility of the decarbonation process and the future demand perspective, adjustment and allocation between industries are negotiated. While some industrial activities

Table 4: Overview of European Union (EU) greenhouse gas (GHG) emissions reduction targets and related carbon budgets in total, per sector and per capita.

	Reference	**Future targets**	
	1990	**2030**	**2050**
EU total			
Reduction targets (%)	100	−46 to −47%[c]	−91 to −94%[c]
GHG emissions (Mt CO_2e/yr)	5650	3060–3091	343–494
Per capita			
EU population	418[d]	449[d]	441[d]
Emissions budget (CO_2e/cap.yr)	13.52	6.81–6.88	0.78–1.12
Per sector			
Power			
(%)	100%	−54 to −68%[b]	−97 to −108%
(Mt CO_2e/yr)	1869[a]	598–860	−141 to 47[c]
Industry			
(%)	100%	−34 to −40%[b]	−96 to −98%
(Mt CO_2e/yr)	1359[a]	815–897	29–53[c]
Residential and services			
(%)	100%	−37 to −53%[b]	−97 to −98%
(Mt CO_2e/yr)	731[a]	344–461	11–13[c]

Notes: [a] Values based on 1990 EU-28 GHG emissions inventory scope under UNFCCC (excluding LULUCF) (EEA 2020).
[b] Sectoral targets for 2030 based on EC (2011).
[c] 2050 based on EC (2018) (Scenarios 1.5TECH, 1.5LIFE and 1.5LIFE-LB).
[d] EU population evolution based on Eurostat (2020).

Table 5: German climate action plan.

CO_2e emissions (Mt/yr)				
Area of action	1990	2014	2030	2050
Energy	466	358	175–183	0
Buildings	209	119	70–72	0
Transport	163	160	95–98	0
Industry[a]	283	181	140–143	17
Agriculture and LULUCF	88	72	58–61	43

Notes: CO_2e emissions reduction targets are split depending on the year and the area of actions. The area of activity is called here 'area of action'. LULUCF = land use, land use change and forestry.
[a] Including waste.
Sources: Data are for 2030 (BMUB 2016) and 2050 (Benndorf *et al.* 2016).

have to reduce their emission by 100%, the construction product industries (steel, aluminium, cement, lime, glass and insulation materials) represent more than 60% of the remaining emissions in 2050 (Benndorf *et al.* 2016). It confirms the fact that these industries are the most difficult to decarbonise as emissions do not come only from the energy related processes but also from raw material-related emissions (*e.g.* limestone decarbonation in cement). Acting only on industry energy efficiency is therefore not possible for construction-related industries and a sufficiency approach is required where the objective is a reduction in material demand (IEA 2019). This material reduction must involve stakeholder beyond industry sector (Favier *et al.* 2018) and this is the reason why design targets and carbon budgets for the embodied part of buildings are needed (see section 4.5).

4.3. Budgets for national or regional building stock

Achieving regional or national GHG reduction targets, including the ones discussed above, is challenging and requires mitigating GHG emissions from both existing and new buildings of a chosen region or country (Giesekam, Tingley, & Cotton 2018; Röck *et al.* 2020). Thus, it is crucial to translate these regional or national GHG reduction targets into meaningful sub-global levels (Bjoern *et al.* 2020; Häyhä *et al.* 2016); the building stock is one of them (Balaras *et al.* 2007; Lavagna & Sala 2018).

Some researchers have already investigated about what these regional or national targets mean to building stocks in different countries (Cuéllar-Franca & Azapagic 2012; Giesekam *et al.* 2018; Lavagna & Sala 2018). However, much of the work is related to the existing buildings in a specific year (or a period) and failed to account for future changes in a building stock such as variations in construction and demolition rates, changes in building sizes, and changes in construction technologies and materials. Accounting for these aspects is critical when assigning a share of the global carbon budget to a chosen building, which can be either an existing building or a future building.

To that end, Chandrakumar *et al.* (2019, 2020b) proposed a top-down based approach for determining carbon budgets for building stocks (and individual buildings), considering the existing national building stock which should be operated in a country from now to a certain time in the future (*e.g.* 2030, 2050) as well as the new building stock that should be constructed in the same period. Their approach translates a chosen global climate target (*e.g.* 1.5 and 2.0°C) into a global carbon budget available from now until a certain time in the future and shared between countries, applying the so-called effort-sharing principle of *cumulative emissions per capita*. This effort-sharing principle is centred on achieving equality in terms of the cumulative GHG emissions of different populations across the world (van den Berg *et al.* 2019; Yu *et al.* 2011) through the contraction and convergence approach.

Subsequently, shares of the country's carbon budget are assigned to the residential as well as non-residential building and construction sectors of the chosen country, using the *grandfathering* effort-sharing principle (van den Berg *et al.* 2019). This principle implies that the carbon budget share (*i.e.* the right to emit GHGs) is determined based on the relative contribution of the sector to the country's total consumption-based GHGs in a chosen reference year (Chandrakumar *et al.* 2020a).

A carbon budget (calculated per 1 m^2 gross floor area) for embodied life-cycle stages is then determined by dividing the carbon budget available for the area of activity related with construction by the total gross floor area of the pre-existing and newly built dwellings that exist in the chosen period. Similarly, a carbon budget (calculated per 1 $m^2 \cdot yr$) for operational life-cycle stages is calculated by dividing the carbon budget for the area of activity related with building operation by the total gross floor area that operate in the same period.

Finally, carbon budgets for different buildings (can be either residential or non-residential) are determined by multiplying the calculated carbon budgets for embodied and operational life-cycle stages with the respective gross floor areas (and the service lives for operational) of the selected buildings.

The proposed approach was recently applied by McLaren *et al.* (2020) to calculate 1.5°C consistent carbon budgets for three common types of residential dwellings in New Zealand, *e.g.* newly built single-family detached house, medium-density house and apartment. According to McLaren *et al.*, the 1.5°C consistent carbon budgets for embodied and operational life-cycle stages are 86 and 61 $kgCO_2$ $e/m^2 \cdot yr$, respectively. Furthermore, the 1.5°C consistent carbon budgets for the whole life-cycle of a typically sized[3] New Zealand newly built single-family detached house, medium-density house and apartment (over a service life of 90 years) are 35, 20 and 17 t CO_2e, respectively.[4] Alternatively, when the 2°C global climate target is chosen, the carbon budgets for the three residential dwellings increased to 50, 29 and 24 t CO_2e, respectively, which is a factor 1.4 increase compared with the 1.5°C consistent carbon budgets.

4.4. Budget for a district

Usual carbon targets are allocated at building scale (SIA 2040:2017; SIA 2017) based on the type of activities (*e.g.* housing, offices) and the intensity of use (number of occupants). This approach allocates a similar carbon budget per m^2 to a building type, without considering the specificity of each project (*e.g.* solar exposure, urban rules). A consideration of a budget at the district scale, which can then be distributed between the buildings depending on their potentials (*e.g.* solar exposure) and their constraints (*e.g.* shape), can better distribute efforts between buildings. To implement this strategy, a method has been developed in Fribourg (Switzerland) and consists of five steps:

(1) The district is divided into zones with similar context (*e.g.* maximum building height, solar exposure), so that buildings within these zones will have similar targets.
(2) For each of these zones, a series of building-level possibilities are generated by defining hypotheses of project-specific parameters and varying design options. The GHG impact of each project alternative is evaluated, thus generating a knowledge database of thousands of options and their corresponding life-cycle impacts.
(3) The average GHG impact of all project design possibilities within one zone is calculated, followed by the calculation of the available GHG impact in accordance with the building area and usage, as defined by SIA2040 norm. Contextual targets are then calculated by attributing the share of the total site impact proportionally to the average impact of each zone (Nault *et al.* 2020).

(4) The method can also be further applied from the building scale towards carbon budget for its systems and components (Jusselme *et al.* 2019) such as the windows and the heating system.

(5) The technical feasibility of reaching a specific contextualised target is thus evaluated and compared with the one of a uniform target. This technical feasibility is an index of performance calculated as the ratio between the number of design options that have a GHG impact lower than the GHG target, and the overall number of design options of the knowledge database.

In **Table 6**, the method is applied to a case study 'Blue Factory' site in Fribourg (Switzerland), which includes eight plots for new buildings (plots A1–D) mixing housing and offices. Results indicate that for the same overall GHG impact at the district level (20 $CO_2e/m^2.yr$), small changes in the target distribution at the zone level leads to a significant increase of the technical feasibility. In zone A1, for instance, increasing by 1.8 $kgCO_2e/m^2.yr$ the GHG target (+9% compared with the uniform target) leads to increase by 29% the feasibility index. To balance the increase of GHG targets, zones C3 and D will have to reach slightly higher performance levels which do not affect significantly their respective feasibility indices (–6.6% and –5.5%). Hence, the allocation of a district-level carbon budget in contextual sub-targets influences significantly the technical feasibility of building-level projects and could offer more flexibility or efficiency in the building design and construction.

4.5. Budgets for a single building

4.5.1. Per capita budget for single building

The application of a per capita budget has been popularised by the Swiss 2000-Watt Society (Zimmermann, Althaus, & Haas 2005). It was first introduced by ETH Zürich in 1998 and envisioned the average First World citizen reducing the overall primary annual energy consumption to 2000 W (which is 48 kWh/day) and 1 tonne CO_2 per capita and per year by 2150 with intermediate target of 2 t CO_2 in 2050. This vision was then adapted considering the urgency of climate action in order to achieve the budget of 1 t CO_2e per capita and year already in 2050 (Hollberg, Lützkendorf, & Habert 2019). However, the 1 t per capita value does not come from a global budget but the assumption that this level is a sustainable emission level, considering current population level and applying a contraction and convergence logic.

A different approach for residential buildings in Czechia focuses on setting an intermediate GHG benchmark for 2030 aligned with the Paris Agreement (Pálenský & Lupíšek 2019). This target is derived from a global yearly allowance for GHG emission in 2030 defined in the *Emissions Gap Report 2018* (Olhoff & Christensen 2018). These annual allowed emissions are then equally distributed per global capita (using a forecasted global population of 8.55 billion in 2030), resulting in 4.68 and 2.81 t CO_2e/year per capita if 2 or 1.5°C targets are chosen.

Once a budget per capita is defined, the next step is to estimate the proportion of the personal GHG allowance to be allocated for individual housing. In Czechia as well as in Switzerland, the estimated share of the current building emission is used as a proxy. However, the definition of 'building emissions' does not cover the same buildings. In

Table 6: Results in terms of uniform and contextual distribution of the greenhouse gas (GHG) targets and relating changes in technical feasibility per zone.

Zone		A1	A2	A3	B	C1	C2	C3	D	Total district
Uniform target	Uniform GWS target ($kgCO_2e/m^2.yr$)	20	20	20	20	20	20	20	20	20
	Number of design options below the target	7297	8355	7948	8740	913	883	1172	1192	–
	Feasibility (%)	55.4	63.4	59.6	66.5	67.5	65.3	86.6	88.1	–
Contextual target	Contextual GWS target ($kgCO_2e/m^2.yr$)	21.8	21.4	21.6	21.4	21.3	22.2	19.1	18.9	20
	Number of design options below the target	11,137	11,210	11,283	10,448	1088	1114	1083	1117	–
	Feasibility (%)	84.5	85.1	84.6	79.5	80.4	82.3	80	82.6	–
Changes in feasibility (%)		29.1	21.7	25	13	12.9	17	–6.6	–5.5	–
Built area per zone (m^2)		3000	6000	4000	10,000	4000	12,000	30,000	35,000	104,000

Note: GWS = global warming score.

Czechia, 23.35% represents an estimated share of the residential building stock to the overall 2014 national CO_2 emissions (Lupíšek 2016).

In Switzerland, emissions cover the six building categories which comprise 80% of the Swiss building stock: residential, administration, school, specialised store, food store and restaurant. The Swiss guide values include building construction, operation and also mobility directly related to the building over the whole life-cycle of a building. The current share of emission was determined for each building category based on the Swiss statistics 2010. Further details are provided in the SIA 2040:2017 (SAI 2017) standard.

Finally, it is possible to reach a budget per building or per m^2 by multiplying the personal building allowance defined previously by the planned number of building occupants, as in Czechia (Lupíšek 2019) or the energy reference area (A_E) per capita, as in Switzerland (SIA 2015). Details are presented in **Table 7**.[5]

Table 8 illustrates the importance and potential for sufficiency strategies to reduce the floor area per resident. As the budget is defined per capita, if there is a smaller area (m^2) per capita, then the GHG budget per area (m^2) would increase (see also Pfäffli *et al.* 2012).

Similar work has been conducted in Denmark. Brejnrod *et al.* (2017) defined climate targets for a single-family house in Denmark (for 2010) at 110 kg CO_2e/cap.yr. They calculated the carbon budget available for a global citizen in 2010 (985 kg CO_2e/cap.yr for 2°C) and assigned a share of it to a Danish single-family house using the sharing principle of final consumption expenditure (*i.e.* the relative share of household expenditure for housing). There is a special relation to the areas of need approach with a carbon budget for individuals and households for 'housing'. Hoxha *et al.* (2020) applied almost the same approach to Kaya's equation for the calculation targets for Austrian context (Nakićenović & John 1991). Using a hybrid top-down, bottom-up approach, they found that the target for the GHGs are of the range of 5.8 kg CO_2e/m^2.yr, comprising 4 kg CO_2e/m^2.yr and 1.8 kg CO_2e/m^2.yr for embodied and operational impacts, respectively.

Similar efforts have also been done to propose climate targets for commercial buildings (Hoxha *et al.* 2016; Russell-Smith *et al.* 2015). For example, Russell-Smith *et al.* (2015) estimated a target of 2.29 t CO_2e/m^2 for the whole life-cycle of a commercial building in the US, considering a 50-year lifetime. The target was based on the GHG emissions projections in the *IPCC Fourth Assessment Report*, which recommended a 70–80% GHG emissions reduction below 1990 levels by 2050 in order for buildings to operate within the 2°C target.

4.5.2. Example illustrating different sharing principles

Andersen *et al.* (2020) investigated absolute environmental sustainability using two approaches: the carrying capacity and the planetary boundaries. Planetary boundaries is a more precautionary approach and sets a lower environmental boundary than the carrying capacity. As sharing principles is a matter of *who* has the right to impact *how much*, six different sharing principles were applied to allocate the carrying capacity and planetary boundaries to a single-family dwelling (Andersen *et al.* 2020). The sharing principles include approaches such as equal per capita, final consumption expenditure, energy consumption and CO_2e emissions. The sharing principles only represent the dwelling share and not the share per m^2. However, the results have been converted here for comparison with other studies. **Table 9** shows how the carbon budget is highly dependent on the sharing principle chosen, varying from 0.67 to 8.84 kg CO_2e/m^2.yr, when the carrying capacity approach is used.

These different results highlight the diversity of approach and the difficulty to define one exact value. When the different proposition for a single building are compared, one can observe a factor 10 between budgets. This is due to all the different assumption possibilities all along the budget definition workflow. Considering the climate emergency and the severe consequences of passing earth climate tipping point will have (Steffen *et al.* 2018), it is very problematic to observe such large differences between countries, which have a relatively comparable level of development. Furthermore, none of the presented budget consider the dynamic of emissions nor the need to first allocate a share of the global budget to essential needs for emerging countries and assess afterward the remaining budget for other area of less urgent needs. They rather adopt a contraction convergence or grandfathering approach, which is unfair (Caney 2009). These two aspects are briefly discussed in the next session.

5. Environmental targets beyond '2050'

5.1. Time conflicts for operation and embodied carbon budgets

Buildings are long-lasting artefacts. The buildings created today are expected to operate far beyond 2050 when buildings will need to be net-zero emissions.

Current net-zero emissions buildings and standards fail to consider the dynamic of emissions. First, they usually focus on compensating operation energy on a yearly basis, but a yearly calculation hides the hourly dynamic and fails to point out the difficulty of daily (Barone *et al.* 2019) and seasonal storage (Kaufmann & Winnefeld 2019; Rostampour *et al.* 2019). The second failure is to consider embodied emissions on a yearly basis. Embodied emissions from construction occur mainly in the first year of the building life time and (approximately 30 years later) when deep renovation are done (**Figure 4**), while operational emissions occur every year at roughly the same rate. The current standard (SIA 2040:2017; SIA 2017) that distributes emissions all along the life time of the building underestimates the peak of emissions which will happen before 2050 exactly when emissions need to be reduced.

Table 7: Calculation details for single-building budget calculation in different countries.

	Switzerland	**Switzerland adapted**	**Denmark**	**Austria**	**Czechia**
Global budget					
Target (Paris Agreement, 2°C, 1.5°C, etc.)			1.5°C (2030)		2 and 1.5°C (2030)
With or without negative emissions			Without negative emissions		Without negative emissions
Budget per country			6.79 Gt CO_2e/yr		24 to 40 Gt CO_2e/yr
Effort-sharing principles					
Historic emissions or not	No historic emissions				
Future or current population	Current Swiss population	Current Swiss population	Current global population	Trend for future population and buildings	Czech population (2030)
Effort-sharing definition (equality, capability)	Equal per capita	Equal per capita	Equal per capita, final consumption expenditure, time spent, energy consumption, CO_2 emissions	Equal per capita	Equal per capita
Budget per capita			2.5 t (2030)		4.68 t (2°C)
(t CO_2e/cap.yr)	2 t (2050)	1 t (2050)	1.4 t (2040)	1 t (2050)	2.81 t (1.5°C)
Allocation principles					
Share of emission per sector	Current share for sectors: 33% for construction and buildings. Feasibility study to split between embodied and operation budget			Current share for sectors: 36% for construction and buildings. Feasibility study to split between embodied and operation budget	Current share of sectors: 23% for residential buildings
Share of m^2 per capita (m^2/capita)	60 m^2 HFA/45 m^2 living space	60 m^2 HFA/45 m^2 living space	39.4 m^2 Gross floor area	67 m^2 HFA	1045 m^2 for 26 occupants (40.2 m^2/capita)
Inhabitants per buildings			2.54		26
Type of activities included	Embodied (construction, maintenance and EoL), operational (electricity and heating)	Embodied (construction, maintenance and EoL), operational (electricity and heating)	Embodied (construction and replacement), operational (water, electricity and heating)	Embodied (construction, maintenance and EoL), operational (electricity and heating)	Embodied (construction, maintenance and EoL), operational (heating)
Related LCA life-cycle stages	A1–A3, B4, B6, C3–C4	A1–A3, B4, B6, C3–C4	A1–A5, B4, B6, B7, C3–C4	A1–A3, B4, B6, C3–C4	A1–A3, B4, B6, C3–C4

(Contd.)

	Switzerland	**Switzerland adapted**	**Denmark**	**Austria**	**Czechia**
Reference study period (yr)	60	60	120	50	
m^2 definition	HFA	HFA	Gross floor area	HFA	Net floor area
Building's budget					
Budget per m² (kg $CO_2e/m^2.yr$)					
Operational budget	3	1.5	0.19–2.5[a]	1.8	
Embodied budget	9	4.5	0.48–6.4[a]	4	
Life-cycle budget (op + emb)	12	6	0.67–8.8[a]	5.8	16.5–26.8
Budget per building (kg CO_2e/yr)					
Operational budget			28.3–371[a]		
Embodied budget			72.1–955[a]		
Life-cycle budget (op + emb)			101.4–1326[a]		17,200–28,300
Reference	Zimmermann *et al.* (2005)	Hollberg *et al.* (2019)	Brejnrod *et al.* (2017)	Hoxha *et al.* (2020)	Pálenský & Lupíšek (2019)

Notes: [a] Variations in budget between the six sharing principles included in the calculations of Andersen *et al.* (2020).
EoL = end of life; HFA = heated floor area.

Table 8: Relation between energy reference area (A_E) and living space per resident and the target values for the budget per capita and year based on the global target of 1 t CO_2e/cap.yr).

Living space (m²)	60	52.5	45	37.5	30
A_E per capita (m²)	80	70	60	50	40
Embodied GHG (kg CO_2e/m².yr)	3.4	3.89	4.5	5.4	6.8
Operational GHG (kg CO_2e/m².yr)	1.1	1.26	1.5	1.8	2.2
Total GHG per m² (kg CO_2e/m².yr)	4.5	5.14	6	7.2	9
Total GHG per capita (kg CO_2e/yr)	360	360	360	360	360

Table 9: Annual carbon budget per m² building (kg CO_2e/m².yr) based on the carrying capacity approach for six different sharing principles (SP).

	SP 1	SP 2	SP 3	SP 4	SP 5	SP 6
Operational budget (kg CO_2e/m².yr)	0.19	0.47	0.3	2.47	1.04	1.17
Embodied budget (kg CO_2e/m².yr)	0.48	1.22	0.77	6.36	2.68	3
Life-cycle budget (kg CO_2e/m².yr)	0.67	1.69	1.07	8.84	3.72	4.16

Note: Derived from results of a household living in a dwelling of 150 m² (Andersen *et al.* 2020). Sharing principle 1 (egalitarian + time shared + final consumption expenditure); Sharing principle 2 (egalitarian + final consumption expenditure); Sharing principle 3 (egalitarian + grandfathering); Sharing principle 4 (grandfathering + energy); Sharing principle 5 (grandfathering + final consumption expenditure); and Sharing principle 6 (final consumption expenditure).

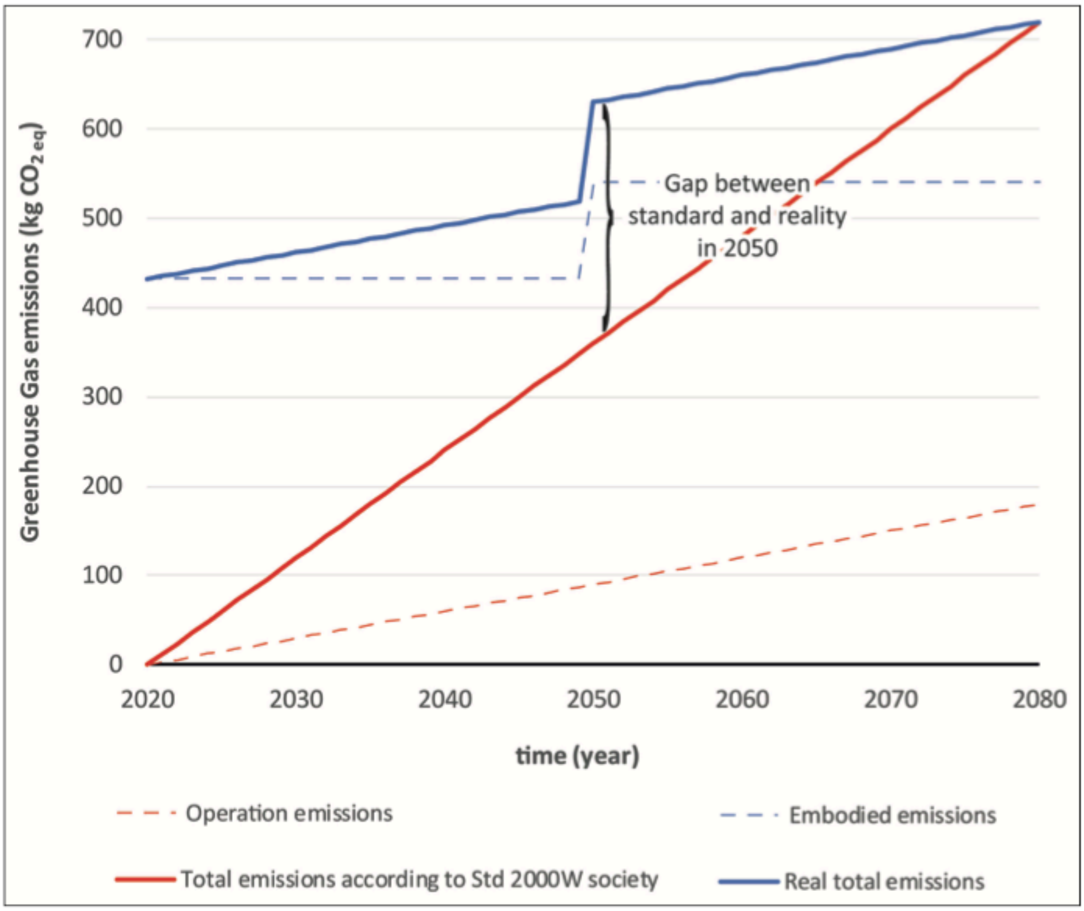

Figure 4: Comparison between operation emissions and embodied emissions for a standard new building according to the 2000 Watt Society standard.

As a consequence, operational emissions can be accounted over the full life-cycle of a building, but should be net zero on an hourly basis in order to be compatible with energy standards post-2050 and construction emissions cannot be allocated and spread over the full life-cycle. Embodied emissions should be counted within the remaining budget at the point in time that they are emitted.

5.2. Carbon investments for enabling a transition

GHG emissions will be needed to build low carbon energy production plants (*e.g.* solar panels, wind turbines) and it is important to avoid lock-in effects by exceeding the available carbon budget through the construction of such infrastructure (Corvellec *et al.* 2013; Shakou *et al.* 2019). The contribution to indirect emissions of infrastructure is generally higher than buildings due to a larger share per m^2 of carbon intensive materials, mainly cement, steel and aluminium (Müller *et al.* 2013). Müller *et al.* (2013) estimate that a budget of 350 Gt of carbon is needed to develop the infrastructure networks in the Global South. This represents already half the total available global budget for all human activities if the 2°C target without negative emissions is considered (**Table 1**). Additional emissions are also to be expected from developed countries where a large share of the existing infrastructure heritage needs to be rehabilitated in the next decades (Hajiesmaeili *et al.* 2019; Vogel *et al.* 2009).

In Europe, the renovation of the building stock has been identified as the main keystone to achieve climate neutrality by 2050. To meet this target, the energy efficiency of existing buildings should be increased by 75% by 2030 and the renovation rate increased to 3%, at least (Sesana, Rivallain, & Salvalai 2020). Thus, a large amount of construction materials, especially thermal insulation, will also be needed to improve the energy efficiency of the building stock (Heeren & Hellweg 2018). If conventional fossil-based materials are used, their embodied carbon risks to consume the remaining carbon budget for EU. However, if the demand of extra insulation were covered by bio-based solutions, especially from fast-growing species (*e.g.* straw, hemp), buildings could act as carbon sinks, providing an extra budget to be spent for the required energy transition and transformation of infrastructure (Pittau *et al.* 2019).

It is fundamental to reconsider all infrastructure projects in the light of their embodied emission level. Low-carbon solutions should be privileged (Hajiesmaeili *et al.* 2019; Pittau *et al.* 2019) and a drastic reduction of the energy demand is required to minimise the need for new infrastructure (Rovers 2019).

5.3. Beyond carbon

Finally, the focus on GHG emissions bears the risk of burden shifting. Beyond the climate crisis, there are many other urgent environmental concerns (*e.g.* biodiversity loss, water scarcity) (IPBES 2019; Rockström *et al.* 2009). A shift towards low-carbon materials and processes (*e.g.* from fossil to renewable energy) may reduce GHG emissions, but increase the pressure on other environmental issues. For renewable energy, the pressure increases particularly on biodiversity, land and water (Desing *et al.* 2019). Specific resources might become critical for a transition towards low carbon economy (de Koning *et al.* 2018; Nansai *et al.* 2014). Reaching the climate target is therefore not sufficient to reach environmental sustainability.

6. Conclusions

The development of a multi-scale carbon budget for buildings is a key policy instrument because it will help the different stakeholders involved all along the value chain of buildings construction and management as well as national regulators to clearly identify their specific targets.

In order to be able to define such cross-sectorial and multi-scale carbon budget, much care is needed in defining what constitutes the object of assessment. Buildings can have many different system boundaries depending on the stakeholder's viewpoint. Transparency along the different steps to define the operating budget is required. In particular, it is fundamental to declare what is the global target chosen, how this global budget is shared among countries and people, how this individual budget is then shared between economic sectors, area of activities and area of needs.

The examples presented in this paper show the feasibility of developing a carbon budget for buildings. However, a similar object of assessment, (with similar overall logic for the budget definition and countries with globally similar level of development) revealed a factor 10 between carbon budgets for single residential buildings. This shows the high sensitivity of hypothesis on the budget definition and the need for clarity in definition and consistency of approach. There are different solutions in place in specific countries—bottom up approach starting from technical and economic feasibility or top down approach, starting from planetary boundary, specific sharing principles or different data sources, among other reasons. Consensus on process is needed to narrow this gap.

Finally, it is clear that the remaining carbon budget should be used in priority to prepare the transition towards post carbon society. Given a clear framework and process it is necessary to develop accurate budget definition. This will enable the creation of equitable and context appropriate legally binding requirements to limit the greenhouse gas (GHG) emissions in the life-cycle of buildings.[6]

Notes

[1] Approximately 50% of the steel production is used for buildings and infrastructure. The other 50% is mainly used for automobile industry.

[2] The authors of this paper conducted an expert workshop in September 2019 in TU Graz (Passer *et al.* 2020).

[3] Gross floor areas for New Zealand's newly built single-family detached house, medium-density house and apartment are 198, 114, and 94 m^2, respectively.

[4] For a detailed description of these dwellings, see Chandrakumar *et al.* (2020b).

[5] The approaches used in the concept of 2000 Watt Society vision do not consider the potential changes of built area over the years. SIA 2040 defines GHG targets for residential buildings based on a fixed value of 60 m^2 energy reference area (A_E) per capita, where A_E is the gross floor area within the thermal building envelope (SIA 2015) and is also used as reference unit for the calculation of the operational energy demand in Switzerland. According to Pfäffli *et al.* (2012), a factor of 1.33 can be used to convert to useful floor area. This value matches the 45 m^2 of average living space reported by the Swiss Federal Office for Statistics (BFS 2016) for 2016.

[6] A recent initiative called the 'Graz Declaration for Climate Protection in the Built Environment' (SBE19 2019) provides guidance to researchers and policy-makers.

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Competing interests

The authors have no competing interests to declare.

Supplemental data

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Article

Carbon Benchmark for Czech Residential Buildings Based on Climate Goals Set by the Paris Agreement for 2030

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Abstract: This paper deals with the problem that actual building regulations do not reflect the climate targets set by the Paris Agreement. To address this, a benchmark was developed for greenhouse gas (GHG) emissions of buildings on the basis of the Emissions Gap Report. We first applied an equal allocation of the GHG emission limit for 2030 among the forecasted population to calculate a virtual personal GHG emission limit. We took a proportion of this personal limit for the purpose of housing and extrapolated it for the whole building based on the number of occupants. We also undertook a case study of an actual multifamily residential building and compared its standard design to the benchmark using a simplified life cycle assessment (LCA) method in line with the national SBToolCZ method. The results showed that the assessed residential house exceeded the emission requirement by a factor of 2.5. Based on the assessment, six sets of saving measures were proposed to reduce the operational and embodied GHG emissions. The saving measures included change in temperature zoning, improvement of the U-values of the building envelope, exchange of construction materials for reduced embodied GHG emissions, exchange of heat source for biomass boiler, introduction of light-emitting diode (LED) lighting, use of mechanical ventilation with heat recovery, addition of vacuum solar collectors, and the addition of photovoltaic (PV) panels. Finally, the variants were compared and their suitability in the Czech conditions was examined.

Keywords: buildings; greenhouse gases; climate change; design stage; residential housing; benchmarks; Paris Agreement; emission gap; simplified life cycle assessment; Czechia; Central Europe

1. Introduction

Climate change is one of the greatest challenges facing humankind. The amount of greenhouse gas (GHG) emissions that society releases into the atmosphere has to be reduced significantly and quickly. Otherwise, there is a risk of unprecedented changes in the atmosphere and consequently in the biosphere and the living conditions for people [1]. Bold actions are therefore needed across all scales and areas of human activities [2,3].

The construction sector, together with the operation of the existing building stock, is a significant emitter of GHG emissions. According to the European Commission, buildings are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the European Union (EU) [4]. At the same time, the potential for delivering significant and cost-effective reductions of GHG emissions in buildings is the highest [5]. To unleash this potential, the EU has implemented the Energy Performance of Buildings Directive (EPBD), which prescribes the energy efficiency levels for new buildings and renovations. The directive has been a significant impetus for recent improvements in energy efficiency of newly designed buildings and retrofitting. However, in the light of climate goals and actions needed to achieve carbon neutrality around 2050, this improvement is still not sufficient. The main problem with the directive is that the performance levels for buildings were set applying a bottom-up approach by tightening the energy efficiency benchmarks that were in place before. The requirement to move towards the climatic goals set by the Paris Agreement [6] is therefore not ensured.

A body of literature has investigated paths to the low- or zero-emission (or carbon-neutral) operation of the building stock of various countries. In 2007, Boardman [7] looked at measures that would reduce the GHG emissions of the UK building stock by 60%. Koo et al. [8] developed an integrated, multiobjective optimization model for establishing a low-carbon scenario to achieve the national carbon emission reduction target for South Korea's residential building sector. Bürger et al. [9,10] investigated the German building stock and its possible pathways to zero-carbon operation by 2050. Lupíšek [11] reviewed proposed deep energy retrofitting scenarios of the Czech building stock and compared the resulting GHG emission savings with the national carbon budget.

There are studies available that optimize the building design in order to significantly reduce the energy demand and related GHG emissions [12] as well as papers that propose ways to design zero-emission buildings [13,14]. This might already be feasible in some locations or specific boundary conditions, but it is not yet the case for the regular construction market. Therefore, benchmarks using a top-down approach that come from the planetary boundaries [15,16] (or carbon budget) to individual buildings need to be derived and tested in real cases so that policymakers can integrate them into national regulatory systems.

This proposal is not new, with benchmarks for construction in Switzerland already being proposed by Zimmermann et al. back in 2005 [17]. However, the problem has gained traction with the increasing focus on climate change. Hoxha [18] followed it up in 2016, and resolving this issue is now one of the main objectives of the ongoing "Annex 72: Assessing life cycle related environmental impacts caused by buildings" of the International Energy Agency's Energy in Buildings and Communities Programme [19]. Hollberg et al. [16] combined the top-down approach, deriving climate benchmarks from the Paris Agreement, with a bottom-up approach based on statistics to create a tool for the optimization of embodied GHG emission in the early building design stages. The topic was discussed in June 2019 at the 71st LCA Forum [20], and it was one of the intensively discussed topics of the Sustainable Built Environment D-A-CH Conference 2019 in Graz. One of the keynote speakers, Head of the Department of Building, Construction Industry and Federal Buildings at the German Federal Ministry of the Interior, Building and Community, Fehn Krestas, mentioned that the German climate sector goals "could be interpreted as the remaining CO2-eq. budget for real estate utilization" [21]. Later on, Chandrakumar et al. [22] introduced top-down targets for New Zealand, and Hollberg et al. [23] showed how to utilize the carbon budget in decision-making in the building design process.

Such a study has been missing for the conditions of Czechia so far, so the main objective of the work presented in this paper was to (i) draft a benchmark in terms of GHG emissions for new buildings, focusing on residential buildings as the largest building segment; (ii) make a case study to compare usual building design with the benchmark; (iii) draft design improvements leading to compliance with the set benchmark; and (iv) evaluate whether the levels of GHG emissions required to fulfill the targets set by the Paris Agreement are workable in the Czech conditions or whether they represent improvements to building design that are too radical and more systemic changes are thus needed in the way we design and construct residential buildings nowadays.

The main contributions of this paper are as follows: (i) promoting the actual idea that some kind of GHG benchmarks at a building level will be needed in the very near future if states want to achieve the climate goals set by the Paris Agreement; (ii) providing an example of how these benchmarks can be set; (iii) presenting a case study showing how we can work with the GHG goals in Czechia; and (iv) discussing how a typical design of a multifamily residential building can be modified to meet the 2030 targets.

This article is based on an MSc thesis by David Pálenský [24], where more details can be found (publicly available but in Czech language only).

2. Materials and Methods

This section describes the setting of the benchmark, the building selected for the case study, the boundary conditions, the procedure of evaluation of the original building design, and the strategy applied to design improvements to comply with the benchmark.

2.1. Setting the Benchmark

As described in the introduction, the objective of the work was to draft a top-down benchmark that would reflect the global GHG emission targets set by the Paris Agreement. As a starting step, we worked with the Emissions Gap Report 2018 (EGR) [25], which dealt with various scenarios of future development of global GHG emissions. It set maximum amounts of global GHG emissions that can be emitted in 2030 so that the rise of the global mean surface temperature still stays below the 2 or 1.5 °C target compared to the preindustrial era. In Table 3.1 on page 19, the EGR states the maximum global amount of GHG emissions in 2030 as 40 Gt CO_{2e} for the 2 °C target and only 24 Gt CO_{2e} to stay below 1.5 °C temperature rise (both with 66% chance), which represents a reduction by approximately one-quarter and more than one-half, respectively, compared to annual GHG emissions.

In order to set the benchmark, the 2030 emissions from the global figure needed to be allocated to individual buildings in Czechia. Debate surrounding which allocation principles of carbon budget or emission allowances should be applied to ensure fairness or which burden-sharing mechanisms should be applied is still ongoing [26–29]. For the purpose of this work, we used equal per capita distribution using the forecast of the world population in 2030 [30]. Once we divided the 2030 annual allowances, i.e., 40 and 24 Gt CO_{2e}, by the forecasted population of 8.55 billion, we got the personal annual allowances of 4.68 and 2.81 t CO_{2e} per capita, respectively.

Finally, as a proxy, we used a figure of 23.35%, which represented an estimated share of the residential building stock on the national CO_2 emissions in 2014 [31] (the calculation behind the figure is presented in [11], which updated the figures slightly for 2015). By multiplying the personal allowance by 23.35%, we arrived at an annual personal 2030 allowance for housing of 1.09 t CO_{2e} for the 2 °C target and 0.66 t for the 1.5 °C target, which could then be extrapolated to an allowance for a residential building by multiplying the figures by the planned number of building occupants.

2.2. Description of the Case Study Building

The building taken for the purpose of this case study was a four-storey residential building with a single rectangular shape and flat roof (see Figures 1–3). The total net floor area of the building was 1045 m^2, and it had 11 flats for 26 occupants in the above-ground floors; the total volume of the building calculated from the external dimensions was 3572 m^3. The ground floor housed a technical room, parking lots, and storage rooms for flats.

The original design, which represented the common standard for new apartment buildings in the Czech market, had a structural masonry wall made of ceramic hollow brick blocks and floor structures made of 230 mm thick ceramic panels. The structure of the double roof with a ventilated cavity was made from massive timber elements. The indoor partition walls were made of hollow bricks and plaster. The structures of staircases were made from reinforced concrete, and the structures of balconies were made of steel. The external walls were insulated by 160 mm thick external thermal insulation composite system made of expanded polystyrene with thin external plaster, and the roof was insulated by 260 mm of glass wool within the timber structure. The mean U-value was 0.47 W/m^2K.

Figure 1. The case study building. Design and visualization by Jan Růžička.

Figure 2. Layout of a typical floor (dimensions in mm).

The heating system consisted of a condensing gas boiler, which heated a central storage tank with a capacity of 750 L, and was coupled with a two-pipe counterflow heat distribution system with panel radiators. The overall ventilation concept was based on natural ventilation, and vacuum ventilation was installed only in rooms with the largest production of pollutants, such as the toilet, bathroom, and kitchen. The air supply was provided by ventilation slots in the windows and peripheral walls. Cooling was not needed.

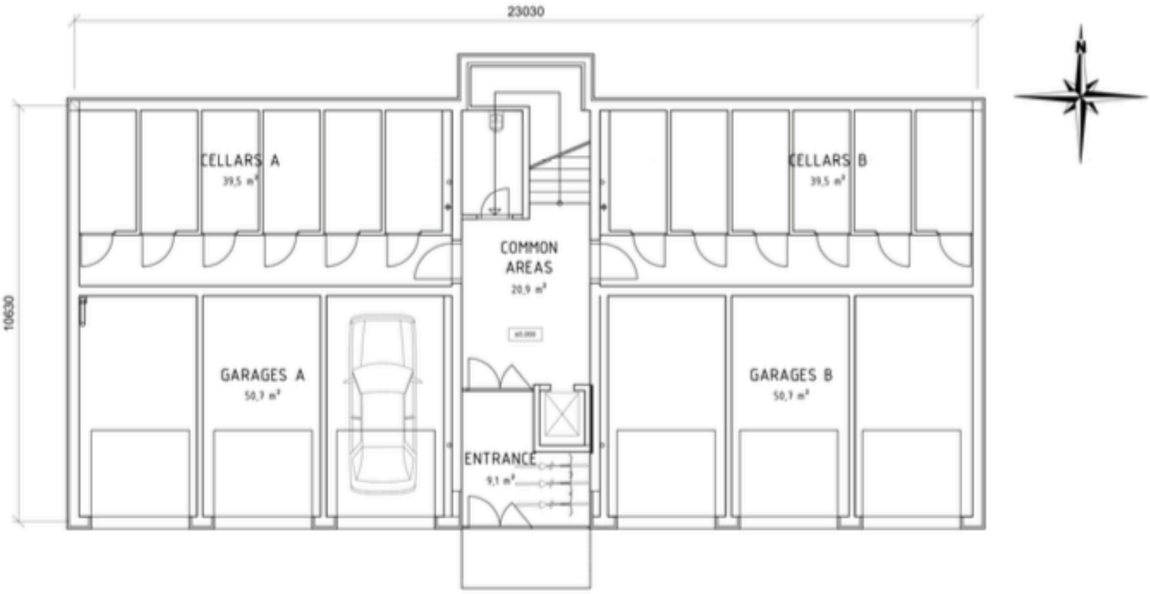

Figure 3. Layout of the ground floor (dimensions in mm).

2.3. Calculation Method for GHG Emissions and Boundary Conditions

For the purpose of this study, we applied a method described in the assessment guidelines of the national sustainability certification scheme SBToolCZ for residential buildings [32,33]. The indicator E.02 global warming potential defines a calculation procedure of the total annual CO_{2e} emissions that comes from a simplified life cycle assessment (LCA) that includes annual operational emissions as well as annualized embodied emissions from life cycle stages A1–A3 and B4. The specific embodied GHG emissions were taken from the ecoinvent database.

The operational emissions of GHG were calculated on the basis of energy modeling and simulations, and the emission factors were determined from the calculated energy consumption and energy carriers. The energy modeling was made using the Czech software Energie 2017 by SVOBODA SOFTWARE according to the national methodology of the Ministry of Industry and Trade Decree No. 78/2013 Coll., which provides a monthly calculation method for energy demand in line with the national standard ČSN 730540-2 and international standards EN ISO 13790, EN ISO 13789, and EN ISO 13370. It includes energy consumption for heating, ventilation, air conditioning, preparation of domestic hot water (DHW), lighting, and auxiliary energy. Consumption of home appliances was not included in the calculation. The production of the energy from the solar collectors was calculated by method B from EN 15316-4-3.

Czechia has an eastern continental climate with cold winters and hot, dry summers. The energy demand for heating was calculated using the monthly average temperatures. The values of total solar irradiation were used for the calculation of the solar gains. Both temperatures and irradiations were taken from the national standard ČSN 73 0331-1 and represented country average data (see Table 1).

The indoor temperature for the living areas was considered as 21 °C. The staircase with adjacent corridors was not considered as heated, but as it gained heat from the apartments, the considered temperature was 16 °C. The ground level with garages was not heated at all and had insulated ceiling; the temperature for this zone was considered 5 °C.

For ventilation, rates of 0.3 h^{-1} (455 m^3/h of fresh air for the whole building) were used. For mechanical ventilation, the calculated efficiency of the heat recovery was 77%. The indoor heat gains from occupants were considered as 2.0 W/m^2 (70% of time) and from appliances as 3.0 W/m^2 (20% of time). Specific energy consumption for lighting in the base variant was 4.4 kWh/m^2, and the figure was 1.9 kWh/m^2 in the improved variants considering light-emitting diode (LED) lighting.

Table 1. External temperatures and total solar irradiations used for the calculation of energy demand for heating in each month (months 1–12 are January–December, respectively).

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
No. of days (-)	31	28	31	30	31	30	31	31	30	31	30	31
Ext. temp. (°C)	−1.3	−0.1	3.7	8.1	13.3	16.1	18.0	17.9	13.5	8.3	3.2	0.5
Irr. north (MJ/m^2)	29.5	48.2	91.1	129.6	176.8	186.5	184.7	152.6	103.7	67.0	33.8	21.6
Irr. south (MJ/m^2)	123.1	184.0	267.8	308.5	313.2	272.2	281.2	345.6	280.1	267.8	163.4	104.4
Irr. east (MJ/m^2)	50.8	91.8	168.8	267.1	313.2	324.0	302.8	289.4	191.9	139.3	64.8	40.3
Irr. west (MJ/m^2)	50.8	91.8	168.8	267.1	313.2	324.0	302.8	289.4	191.9	139.3	64.8	40.3
Irr. horizon (MJ/m^2)	74.9	133.2	259.9	409.7	535.7	526.3	519.5	490.3	313.6	203.4	90.7	53.6

The calculation of the energy for DHW preparation was considered as 35.0 L per person and day, which totaled 332.2 m^3 of the DHW per year (heated from 10 to 55 °C). Auxiliary energy included the energy of pumps and monitoring and control systems of the heating system. The gas condensing boiler and the pellet boiler had a calculated efficiency of 95% and 86%, respectively.

The emission factors for the energy carriers were taken from the SBToolCZ assessment guidelines [32]: electricity 207.4 g CO$_{2e}$/MJ, natural gas 87.1 g CO$_{2e}$/MJ, and wood pellets 9.2 g CO$_{2e}$/MJ (in Czechia, biomass from wood waste is regarded as renewable source of energy, fulfilling the carbon neutrality criteria by the Intergovernmental Panel on Climate Change (IPCC)).

The basis of the evaluation of embodied GHG emission was a compilation of the bill of quantities of major building elements. Values of GHG emissions for the materials and building products used were obtained from the catalogue of physical and environmental profiles of construction elements for new buildings and reconstructions (envimat.cz) [34]. In line with the assessment guidelines, the following elements were included in the calculations:

- foundation,
- waterproofing layers,
- compacted fill, backfill material (imported from the place outside the building),
- vertical and horizontal construction elements, including overhanging structures,
- roof construction,
- roof deck,
- staircase,
- railing,
- internal partitions,
- nonbearing cladding,
- finishes,
- final floor covering,
- windows and doors,
- thermal and acoustic insulation.

On the other hand, small finishing elements (laths, metal elements, handles, and others) and building service systems were not included.

The reference study period for the simplified LCA was 50 years, and the modeled service lives of the building elements followed the recommendations listed in the assessment guidelines for each category of materials or products. At the end of the calculation, all embodied emissions were summed up and divided by 50 years to get the annualized embodied value.

3. Results

3.1. GHG Emissions of the Case Study Building Designed in the Usual Fashion

The calculated total annual energy consumption of the case study building designed in the usual fashion was 101.7 MWh. More than two-thirds of the energy was used for heating (69.9 MWh/a), slightly more than one-quarter was used for preparation of DHW (28.4 MWh/a), 2.8 MWh/a was used for lighting, and 0.6 MWh/a was used for auxiliary energy consumption. Most of the modeled energy consumption was delivered by natural gas (98.3 MWh/a), and only 3.4 MWh/a was supplied in electricity.

3.2. Measures Proposed to Reduce GHG Emissions of the Initial Design

The following measures were proposed to reduce embodied and operational GHG emissions:

- M1: Change in temperature zoning—nonresidential premises converted to unheated or only semiheated.
- M2a: Reduction of heat losses—thermal insulation of external structure based on the U-values required for passive houses by ČSN 730540 (external walls 0.18 W/m^{2}K, roof 0.15 W/m^{2}K, windows 0.71 W/m^{2}K, doors 1.50 W/m^{2}K), optimization of thermal couplings (0.02 W/m^{2}K).
- M2b: Reduction of heat losses—thermal insulation of external structure based on the U-values recommended for passive houses by ČSN 730540 (external walls 0.12 W/m^{2}K, roof 0.10 W/m^{2}K, windows 0.55 W/m^{2}K, doors 1.50 W/m^{2}K), maximum optimization of thermal couplings (0.02 W/m^{2}K).
- M3a: Reduction of embodied emissions—choice of environmentally friendly products and materials (sand–lime bricks for wall structures and reinforced concrete prestressed hollow panels for ceiling structures).
- M3b: Reduction of embodied emissions—choice of environmentally friendly products and materials (timber structure: two-by-four system).
- M4: Low-emission heat—choice of low-emission source/energy carrier (wood biomass boiler).
- M5: Lighting—installation of energy-saving fluorescent and LED luminaires.
- M6: Mechanical ventilation with heat recovery (efficiency 77%)—reduction of heat losses by ventilation, utilization of waste heat.
- M7: Vacuum solar collectors—use of solar energy for preheating of DHW (80 m^2).
- M8a: Photovoltaic panels—use of solar energy to cover electricity demand (30 m^2), 5.4 kWp, system efficiency 15%, south-facing 35°.
- M8b: Photovoltaic panels—use of solar energy to cover electricity demand (50 m^2), 9.0 KWp, system efficiency 15%, south-facing 35°.

3.3. Variant Sets of the Improvement Measures

The following six variant sets of the improvement measures were designed (a summary of the sets is provided in Table 2):

- **S1** (M1, M4, M5): S1 was a combination of basic measures with minimum changes in the functioning of the building or changes in the design (biomass boiler, efficient LED lighting, and decrease of the internal temperature in the main corridors). The measures were aimed at reducing the amount of operational GHG emissions.
- **S2** (M1, M3a, M4, M5, M7): S2 complemented the previous option S1, with an emphasis on reducing the share of embodied GHG emissions using a construction system in the form of sand–lime bricks for wall structures and reinforced concrete prestressed cavity panels for ceiling structures. The variant was also supplemented by a system of vacuum solar collectors used for the preparation of DHW (80 m^2, south facing 35°, combined with accumulation tank 4500 L).

- **S3** (M1, M2a, M3b, M4, M5, M6, M7): S3 combined the proposed measures with an emphasis on the low-energy performance of the building. All constructions met the required heat transfer coefficient values for passive buildings; thermal couplings and bridges were optimized to minimum values. The technical systems were supplemented by a forced equilibrium ventilation system with heat recovery. The construction system was newly designed as a timber building in a two-by-four system in the form of a prefabricated wooden frame filled with thermal insulation. The ceiling construction was a wooden beamed ceiling.
- **S4** (M1, M2a, M3b, M4, M5, M6, M7, M8a): S4 was based on a combination of the measures mentioned in S3. In addition, a system of photovoltaic panels was used for reducing electricity consumption that would be increased by forced ventilation systems and solar collector pumps.
- **S5** (M1, M2a, M3b, M4, M6, M7, M8a): S5 was based on a combination of the measures mentioned in S4, with the difference that the heat source was the original gas condensing boiler.
- **S6** (M1, M2b, M3b, M5, M6, M7, M8b): S6 was built on S5 to meet the emission requirement while maintaining the original heat source in the form of a gas condensing boiler (S5 did not meet the emission requirement). The combination of measures was based on S5 with a few fundamental differences. The envelope structures were designed for the lowest values of the recommended values $U_{pas,20}$ for passive buildings according to ČSN 73 0540-2. The thermal couplings were reduced as much as possible. The photovoltaic (PV) modules were used to cover the consumption of electrical energy for the operation of forced ventilation, auxiliary energy, lighting, and parts of the hot water production. The surpluses were fed to the energy grid (although we did not consider these surpluses in the operating emission balance). Compared to the previous variants, the total area of the panels increased to 50 m^2.

Table 2. Overview of the six sets of greenhouse gas (GHG) emission-saving measures.

	Original State	S1	S2	S3	S4	S5	S6
GHG Emission-Saving Measures							
M1 Change in temperature zoning		✔	✔	✔	✔	✔	✔
M2a U-values required for passive housing				✔	✔	✔	✔
M2b U-values recommended for passive housing							
M3a Sand–lime bricks, prestressed concrete floor structures			✔				
M3b Timber structure				✔	✔	✔	✔
M4 Biomass boiler		✔	✔	✔	✔		
M5 LED lighting		✔	✔	✔	✔	✔	✔
M6 Mechanical ventilation with heat recovery				✔	✔	✔	✔
M7 Vacuum solar collectors 80 m^2			✔	✔	✔	✔	✔
M8a PV panels 5.4 kWp, 30 m^2					✔	✔	
M8a PV panels 9.0 kWp, 80 m^2							✔
U-Values of the Building Envelope (W/m^{2}K)							
External wall (heated area)	0.27	0.27	0.27	0.18	0.18	0.18	0.12
External wall (unheated area)	0.62	0.62	0.62	0.38	0.38	0.38	0.38
External wall—plinth (unheated area)	0.57	0.57	0.57	0.38	0.38	0.38	0.38
Floor above unheated ground floor	0.57	0.57	0.57	0.38	0.38	0.38	0.16
Floor on the ground	0.56	0.56	0.56	0.45	0.45	0.45	0.45
Roof	0.21	0.21	0.21	0.15	0.15	0.15	0.10
Windows	1.50	1.50	1.50	0.71	0.71	0.71	0.55
Entrance door	3.50	3.50	3.50	1.50	1.50	1.50	1.50
Overhead doors (garages)	3.50	3.50	3.50	1.50	1.50	1.50	1.50
Thermal couplings	0.05	0.05	0.05	0.02	0.02	0.02	0.00

3.4. GHG Emissions of the Proposed Variants

A breakdown of the embodied emissions and the modeled energy consumption and GHG emissions of the proposed sets are summarized in Table 3.

Table 3. Modeled embodied GHG emissions, energy consumptions, and GHG emissions of the original building (business as usual) and proposed sets of improvements S1–S6.

	Original State	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Embodied GHG Emissions (t CO_{2e})							
Foundations	58.1	58.1	58.1	64.6	64.6	64.6	64.6
External walls	64.9	64.9	63.0	33.3	33.3	33.3	37.1
Internal walls	52.0	52.0	41.6	13.5	13.5	13.5	13.5
Horizontal structures	216.2	216.2	156.2	99.0	99.0	99.0	103.1
Other components	32.4	32.4	32.4	69.1	69.1	69.1	69.1
Total	**423.5**	**423.5**	**351.2**	**279.5**	**279.5**	**279.5**	**287.4**
Annual Energy Consumption (MWh/a)							
Heating	69.9	80.7	80.7	38.6	38.6	34.1	16.6
Domestic hot water	28.4	31.3	29.3	29.3	29.3	27.7	27.7
Vacuum solar collectors	0.0	0.0	−12.3	−12.3	−12.3	−12.5	−12.3
Mechanical ventilation	0.0	0.0	0.0	1.5	1.5	1.5	1.5
Lighting	2.8	1.8	1.8	1.8	1.8	1.8	1.8
Photovoltaic panels	0.0	0.0	0.0	0.0	−3.2	−3.2	−7.4
Auxiliary energy	0.6	0.4	0.8	0.8	0.8	0.8	0.7
Total	**101.7**	**114.2**	**100.3**	**59.7**	**56.5**	**50.2**	**28.6**
Operational GHG emissions (t CO_{2e}/a)	33.36	5.35	5.57	5.30	3.25	16.87	10.45
Annualized embodied GHG emissions (t CO_{2e}/a)	8.47	8.47	7.02	5.59	5.59	5.59	5.75
Total annual GHG emissions (t CO_{2e}/a)	**41.8**	**13.8**	**12.6**	**10.9**	**8.8**	**22.5**	**16.2**
Compliance with target 28.3 t CO_{2e}/a (target 2.0 °C)	X	✔	✔	✔	✔	✔	✔
Compliance with target 17.2 t CO_{2e}/a (target 1.5 °C)	X	✔	✔	✔	✔	X	✔

Set S1 included replacement of the condensation gas boiler with a biomass boiler, installation of efficient LED lighting, and reduction in the internal temperature in the main corridors. These measures contributed to a significant drop in the operational GHG emissions due to savings in electricity consumption and the low-emission factor of the biomass, i.e., 9.2 g CO_{2e}/MJ (compared to the electricity emission factor 207.4 g CO_{2e}/MJ). On the other hand, it increased the total consumption of energy due to the reduced energy efficiency of the boiler (pellet boiler 86%, original gas boiler 95%), the efficiency of heat distribution (pellet boiler 85%, original gas boiler 98%), and reduced internal heat gains from lighting.

Set S2 built upon S1 and reduced embodied GHG emissions by replacing the structural wall material made of standard brick blocks to sand–lime bricks and prestressed hollow concrete panels. The achieved reduction was 72.3 t CO_{2e}. This set also benefited from the addition of the vacuum solar collectors, which delivered 12.3 MWh of clean energy.

Set S3 combined the measures applied in S2 with significant improvement in the U-values of the building envelope, the addition of mechanical ventilation with heat recovery, and use of timber structure for construction. The improved U-values led to a significant reduction of heat consumption, while the introduction of mechanical ventilation caused a significant increase in the consumption of electricity, which resulted in high operational GHG emissions due to the high emission factor. The transformation of the design to a timber structure reduced the total embodied GHG emissions by another 71.7 t CO_{2e}.

Set S4 was similar to S3 but also took advantage of the PV system (5.3 kWp), which delivered an additional 3.2 MWh of clean electricity. Thus, it enabled the reduction of operational GHG emissions by 2.05 t CO_{2e}.

Set S5 was a reaction to a situation where a biomass boiler could not be used due to local particular matter emission regulation. It had all the features of S4 but used gas condensing boiler instead of pellet boiler. In this variant, the building was compliant with the 2 °C emission target but not with the 1.5 °C target.

Set S6 included measures that were needed to achieve the 1.5 °C emission target, i.e., further improvement of the U-values of the building envelope and further extension of the PV system, which achieved the limits of the roof surface area. As a result, the operational emissions decreased to 10.45 t CO_{2e}, which enabled achievement of the target.

4. Discussion

4.1. GHG Benchmarks for Buildings

In an ideal world, GHG benchmarks would not be needed because all environmental externalities of human activities would be included in the price of every product so that consumers and investors get price signals that signify behavior that is favorable for society. Another solution would be a global carbon tax or global emission trading scheme that would include human activities and thus modify the economic system in such a way that only sustainable behavior is profitable. However, at present, this is not happening in the world. Therefore, we need some kind of regulation for the building sector, and such regulation could be based on GHG benchmarks.

The presented GHG benchmark for residential buildings suffered from various simplifications, imperfections, and uncertainties. The main simplification lies in the fact that we used an equal allocation of the remaining carbon budget (and thus allowance for annual GHG emissions). As mentioned in the introduction, the debate around which kind of allocation should be used is still ongoing, and the preferred allocation principle might be revised in the future in either direction. The carbon budget allocated to people living in Czechia might be greater because our current per capita is high, and reducing it massively in just a few years would cause a shock. However, it might also be lower because Czechia (and former Bohemia within the Austrian Empire and Czechoslovakia) has been a highly industrialized country since the beginning of the 20th century, so the country has historically contributed to climate change relatively more than developing countries, which should have the right to develop. The result of this debate remains to be seen, and therefore we opted for equal per capita allocation.

Another source of uncertainty is in the remaining carbon budget itself as it changes over time, and the pace of its depletion is variable. Knowledge of climate change also evolves over time, and continuous adjustments would be needed.

There is also uncertainty related to the share of the Czech residential building stock in the total national emissions as the underlying study was based on an estimation based on a model of the Czech building stock that suffers from uncertainties. Furthermore, total national emissions are statistical figures that suffer from some level of uncertainty.

However, even given these uncertainties, we still believe that the exercise was worthwhile because it highlighted the huge gap between the common building design of the construction practice and the practice that needs to be adopted to achieve climate goals.

4.2. Uncertainties in the Case Study

The case study suffered from standard uncertainties of a simplified LCA: uncertainties in the underlying data on materials, emission factors, modeled scenarios, approach to annualization of embodied emissions based on the reference study period as well as uncertainties related to energy modeling using the monthly method.

The calculation of the energy balance of the photovoltaic system and its usability was simplified. For more accurate calculations, it would be necessary to use specialized software with regard to the surplus electricity generated from the PV, which was fed back to the energy grid. When a more detailed simulation is made, the question arises as to whether or not emission balance is to be considered and which emission factor is to be applied (real energy mix and, thus, the emission factor varies in time).

The energy rating of the building did not include the consumption of electricity for standard and nonstandard appliances. Due to the high emission factor of electricity in Czechia, this consumption can have a significant impact on the value of the total operational emissions.

4.3. Applicability of the GHG Emission Reduction Strategies from the Case Study

The applied GHG emission reduction strategies followed two principles: providing energy from sources with a low emission factor and reducing energy consumption. Therefore, we first tried to make minimum changes to the original design, simply swapping the gas boiler for the pellet boiler. In terms of GHG emissions, this would help a lot (given that there is a sustainable source of wood). However, the pellet boiler has reduced efficiency, which would lead to increased energy consumption. At the same time, in many Czech municipalities, there is problem with air pollution. Therefore, installing pellet boilers, a particular source of pollution, would not even be allowed. Therefore, we set up the other sets of measures, which would be widely applicable but would represent more significant changes to the design of a building. Even these variants might suffer from another kind of limitation. In some locations, large PV systems with limited grid capacity would not be allowed to be connected to the grid, and some kind of on-site electricity accumulation would therefore be needed.

Furthermore, in the study, when proposing the variant sets of measures, some of the properties of the original building were not fully considered—for instance, fire resistance or acoustic parameters of the proposed solutions were not calculated or compared to the building in its original state.

5. Conclusions

This paper presented a possible approach to the application of top-down GHG emission benchmarks on residential buildings in Czechia set on the basis of the Emissions Gap Report, equal allocation of limits to GHG emissions for 2030 among the forecasted population, and the share of residential buildings on national emissions.

An actual design of a multifamily residential building was used to compare GHG emissions from a common building design to the benchmark using a simplified LCA method in line with the national SBToolCZ method. The results showed that the assessed residential house designed in a standard fashion exceeded the emission limit by a factor of 2.5. Based on the assessment, six sets of saving measures were proposed to reduce the operational and embodied GHG emissions. The saving measures included change in temperature zoning, improvement of U-values of the building envelope, exchange of construction materials for reduced embodied GHG emissions, exchange of heat source for biomass boiler, introduction of LED lighting, use of mechanical ventilation with heat recovery, addition of vacuum solar collectors, and the addition of PV panels. Finally, the variants were compared and their suitability in the Czech conditions was examined.

The presented principles are applicable to situations in other countries as well, even though there are still many sources of uncertainties.

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