Supplementary Material

Potential of Substituting Softwood with Hardwood – A Resource-Based Analysis

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Table S1. Data Availability, Data Reliability and Used Data

Report or statistics	Information included	Reliability
wood market report of the German Federal Ministry of Food and Agriculture (BMEL, 2014, 2015, 2016, 2017c; BMELV, 2008, 2009, 2010, 2011, 2012, 2013)	wood harvest, producer price index, production volume of wood products, imports and export, etc.	wood harvest: underestimation because private forest owners have no reporting obligation no differentiation between hardwood assortments within import and export no differentiation between soft- and hardwood within import and export of wood fuels and by-products
production statistics of the German Federal Statistical Office	Production volume of hardwood based-products	underestimation due to cut-off threshold by company size (employee or/and turnover) not every reporting company is reporting every year, production volumes are missing or not listed
working paper of raw wood and semi-finished wood products of the German Federal Statistical Office	consumption, stocks, production volume of German sawmill, veneer, plywood and wood panel industry	full survey with cut-off threshold by company size (employee or/and turnover) inaccuracy due to the cut-off threshold and missing answers (e.g., too late) within some years consumption and production volumes are missing or not listed
statistical annual report of the German Federal Ministry of Food and Agriculture	wood consumption of wood processing industries, production volume of wood products, imports and export, etc.	non-continuous data, e.g., only the years 2005, 2010, 2012, 2014 ~ 2017 are listed missing data (within listed years)
energy statistics of the German Federal Statistical Office	electricity and heat production	renewable sources are only separated in biogenic solid fuels no separate differentiation of wood share within energy production
studies and fuel surveys of Döring et al. (2018a), Döring et al. (2018b), Döring et al. (2016) and Mantau (2012c)	consumption of wood in energy production	complete surveys of wood consumption within energy production in heat and power stations and in private households partial differentiation between softwood and hardwood iterations approximately every five to ten years, but not in the same year for private households and heat and power plants
Forestry Production and Trade (FAOSTAT, 2018)	wood production by assortments, wood product production and trade, statistical report generated by a database query	wide range of countries, values, specifications and years no differentiation between hardwood assortments within import and export no differentiation between soft- and hardwood within import and export of wood fuels and by-products partly different forestry and wood product codes compared to the wood market report or the official production statistics
wood resource monitoring (Döring et al. (2018a), Döring et al. (2018b), Zimmermann et al. (2018), Döring et al. (2017a), Döring et al. (2017b), Döring et al. (2017c), Döring et al. (2016), Mantau et al. (2013), Döring and Mantau (2012), Mantau (2012a), Weimar et al. (2012), Mantau et al. (2007), Sörgel and Mantau (2006)	wood flow analysis and wood resource balances for Germany	complete survey for the wood based sector as single branch studies estimations of wood production volumes below the cut-off thresholds iterations approximately every five years, but not in the same year for every branch partial differentiation between softwood and hardwood no separate investigation of the veneer industry wood resource balances include all wood species, for some sectors a differentiation in soft- and hardwood
Annual report of the German Pulp and Paper Association (VDP)	pulp and paper production, used raw materials	underestimation due to cut-off threshold by company size (employee or/and turnover) within the official production statistics members of the VDP are reportable to the association
Production reports of the German fuel wood and pellet association (DEPV)	production, consumption, import and export of pellets	underestimation due to cut-off threshold by company size (employee or/and turnover) within the official production statistics members of the DEPV are reportable to the association

Table S2. Conversion Factors (Weimar, 2011)

Product	Unit	Conversion factor for m^3 (f)
roundwood	m^3 under bark	1.00
fuelwood (firewood, wood chips)	m^3 under bark	1.00
garden wood	m^3 under bark	1.00
by-products / processing residues	m^3	1.00
hardwood by-products / processing residues	t air dry	1.42
post-consumer wood	t air dry	1.82
sawn wood	m^3	1.00
Veneer	m^3	1.00
Plywood	m^3	0.96
particleboard	m^3	1.25
MDF	m^3	1.39
fibre boards	m^3	1.47
chemical pulp	t	2.13
wood pellets	t	2.22
wood briquettes	t	2.22
charcoal	t	1.65

Table S3. Overview and Comparison of Given and Calculated Variables, Processes and Transfer Coefficients (BD = subprocess stock delta, BI = subprocess stock input, BO = subprocess stock output, BS = subprocess total stock, FW = flow value, TC = transfer coefficient, TS = sum of transfer coefficients)

Short name	Code	Description	Input Flow value	Input Standard uncertainty	Output flow value	Output standard uncertainty
BaEP<1MW	FV:186	Bark for the EP < 1 MW			0.04	0.00
BaEP>1MW	FV:185	Bark for the EP > 1 MW			0.52	0.02
BaPI	FV:251	Bark from the panel industry	0.19	0.01	0.19	0.01
BaPP	FV:249	Bark from the plywood production			0.02	0.00
BaPuI	FV:250	Bark from the pulp industry			0.03	0.00
BaSI	FV:246	Bark from the sawmill industry			0.31	0.02
BaVI	FV:247	Bark from the veneer industry			0.03	0.01
BaVP	FV:248	Bark from the veneer production			0.02	0.01
BE	FV:265	Briquettes exported	0.00	0.00	0.00	0.00
BI	FV:263	Briquettes imported	0.07	0.01	0.07	0.01
BrEP	FV:162	Briquettes for the energy production			0.14	0.02
ByPBrP	FV:164	By-products for the briquette production	0.04	0.02	0.02	0.02
ByPE	FV:84	By-products exported	0.38	0.02	0.38	0.02
ByPEP	FV:132	By-products for the energy production			0.31	0.02
ByPEP<1MW	FV:142	By-products for the EP < 1 MW	0.10	0.01	0.10	0.01
ByPEP>1MW	FV:138	By-products for the EP > 1MW	0.16	0.02	0.16	0.02
ByPEPI	FV:120	By-products for the energy product industry	0.34	0.02	0.31	0.01
ByPFWP	FV:91	By-products from the further wood processing			0.06	0.00
ByPI	FV:90	By-products imported	0.39	0.03	0.39	0.03
ByPP	FV:71	By-products from the plywood production			0.07	0.01
ByPPaI	FV:111	By-products for the panel industry	0.54	0.02	0.54	0.02
ByPPEP	FV:147	By-products for the PEP	0.05	0.01	0.05	0.01
ByPPP	FV:163	By-products for the pellet production	0.30	0.02	0.29	0.01
ByPPuI	FV:109	By-products for the pulp industry	0.15	0.01	0.15	0.01
ByPSI	FV:80	By-products from the sawmill industry			1.11	0.06
ByPVI	FV:79	By-products from the veneer industry			0.13	0.03
ByPVP	FV:70	By-products from the veneer production			0.06	0.03
CCCE	FV:218	Charcoal consumed and exported	0.18	0.00	0.18	0.00
EP	FV:127	Energy produced			21.53	0.56
EP<1MW	FV:134	Energy production in plants < 1 MW			2.44	0.15
EP>1MW	FV:133	Energy production in plants > 1 MW			5.04	0.18
EPE	FV:160	Pellet exported			0.07	0.01

EPEP<1MW	FV:145	Energy products for the EP < 1 MW	0.08	0.01	0.09	0.01
EPEP>1MW	FV:136	Energy products for the EP > 1MW	0.01	0.00	0.01	0.00
EPI	FV:166	Energy products imported			0.13	0.01
EPP	FV:128	Energy products produced			0.44	0.02
EPPEP	FV:148	Energy products for the PEP	0.29	0.03	0.35	0.02
FFU	FV:170	Fellings from forests unrecorded			9.00	0.52
FLGEP	FV:262	Fire logs from gardens for the energy production	0.90	0.03	0.90	0.03
FPSWPC	FV:85	Further processed sawnwood consumed	0.56	0.03	0.56	0.02
FRPF	FV:229	Fellings recorded private-owned forests	4.53	0.20	4.53	0.12
FRSF	FV:228	Fellings recorded state-owned forest	8.74	0.23	8.74	0.15
FWC >1MW	FV:143	Forest wood chips for the EP > 1MW	0.98	0.16	0.98	0.16
FWC<1MW	FV:139	Forest wood chips for the EP < 1 MW	1.28	0.07	1.28	0.07
FWCEP	FV:188	Forest wood chips for the energy production			2.52	0.18
FWCEPP	FV:194	Forest wood chips for the PEP	0.26	0.05	0.26	0.05
HDFP	FV:253	HDF produced	0.83	0.05	0.83	0.05
LCW PEP	FV:258	Landscape care wood for the PEP	0.14	0.32	0.14	0.32
LCWEP	FV:259	Landscape care wood for the energy production			1.75	0.35
LCWEP<1MW	FV:260	Landscape care wood for the EP<1MW	0.67	0.13	0.67	0.13
LCWEP>1MW	FV:261	Landscape care wood for the EP>1MW	0.94	0.03	0.94	0.03
LDFP	FV:254	LDF production	0.12	0.01	0.12	0.01
MDFP	FV:252	MDF produced	0.45	0.11	0.45	0.11
PBP	FV:113	Particleboards produced	1.66	0.07	1.66	0.07
PCCP	FV:217	Pulpwood for the charcoal production			0.18	0.00
PCW	FV:115	Post-consumer wood			2.66	0.04
PCWEP	FV:130	Post-consumer wood for the energy production			2.27	0.04
PCWEP >1MW	FV:137	Post-consumer wood for the EP > 1MW	2.00	0.04	2.00	0.04
PCWEP<1MW	FV:141	Post-consumer wood for the EP < 1 MW	0.04	0.01	0.04	0.01
PCWPaI	FV:117	Post-consumer wood for the panel industry	0.39	0.02	0.39	0.02
PCWPEP	FV:146	Post-consumer wood for the PEP	0.23	0.02	0.23	0.02
PE	FV:237	Pulpwood exported	0.69	0.03	0.69	0.03
PeEP	FV:161	Pellets for the energy production			0.29	0.02
PEP	FV:135	Private energy production			14.06	0.51
PEPI	FV:119	Pulpwood for the energy product industry			0.19	0.00
PEx	FV:266	Pellets exported	0.06	0.01	0.07	0.01
PI	FV:264	Pellet imported	0.07	0.00	0.07	0.00
PIm	FV:231	Pulpwood imported	0.31	0.02	0.31	0.02
PPaI	FV:112	Pulpwood for the panel industry			2.32	0.14
PPF	FV:233	Pulpwood from private-owned forests	1.14	0.10	1.14	0.09
PPP	FV:216	Pulpwood for the pellet production	0.01	0.00	0.01	0.00
PPuI	FV:108	Pulpwood for the pulp industry			0.25	0.03
PSF	FV:232	Pulpwood from state-owned forests	3.00	0.11	3.00	0.10
PUn	FV:234	Pulpwood unrecorded			2.52	0.15
PuP	FV:110	Pulp production	0.37	0.03	0.37	0.03
PUS	FV:244	pulpwood unknown sink			3.52	0.21
PWC	FV:94	Plywood consumed	0.08	0.01	0.08	0.01
RE	FV:238	Roundwood exported			1.38	0.05
RI	FV:230	Roundwood imported			0.63	0.03
SLSI	FV:77	Sawlogs for the sawmill industry			3.09	0.17
SVLE	FV:235	Sawlogs/veneer logs exported	0.65	0.05	0.65	0.05
SVLI	FV:226	Sawlogs/veneer logs imported	0.29	0.02	0.29	0.02
SVLPF	FV:225	Sawlogs/veneer from private-owned forests	1.26	0.05	1.26	0.05
SVLSF	FV:227	Sawlogs/veneer logs from state-owned forests	2.60	0.11	2.60	0.10
SVLUn	FV:224	Sawlogs/veneer logs unrecorded			2.25	0.13
SVLUS	FV:245	sawlogs/veneer logs unknown sink			2.34	0.20
SWC	FV:83	Sawnwood consumed			0.70	0.11
SWE	FV:93	Sawnwood exported	0.67	0.05	0.67	0.05
SWFSWP	FV:81	Sawnwood for the further sawnwood processing	0.31	0.03	0.31	0.03
SWI	FV:92	Sawnwood imported	0.32	0.05	0.32	0.03

SWP	FV:98	Sawnwood produced			1.68	0.09
VL	FV:78	Veneer logs			0.32	0.07
VLPP	FV:73	Veneer logs for the plywood production			0.17	0.02
VLVP	FV:72	Veneer logs for the veneer production			0.15	0.06
VSC	FV:86	Veneer sheets consumed	0.07	0.03	0.07	0.03
WFE	FV:243	Wood fuel exported	0.04	0.00	0.04	0.00
WFEP	FV:169	Wood fuel for the energy production			12.78	0.40
WFEP<1MW	FV:189	Wood fuel for the EP < 1 MW	0.22	0.03	0.22	0.03
WFEP>1MW	FV:151	Wood fuel for the EP > 1 MW	0.43	0.08	0.43	0.08
WFEPI	FV:123	Wood fuel for the energy product industry	0.06	0.00	0.06	0.00
WFI	FV:242	Wood fuel imported	0.03	0.00	0.03	0.00
WFPEP	FV:150	Wood fuel for the PEP	12.13	0.39	12.13	0.39
WFPF	FV:222	Wood fuel from private-owned forests	2.13	0.12	2.13	0.10
WFSF	FV:221	Wood fuel from state-owned forests	3.14	0.13	3.14	0.12
WFUn	FV:223	Wood fuel unrecorded			4.23	0.24
WFUS	FV:240	Wood fuel unknown sink			6.98	0.26
WNFA	FV:257	Wood from non-forest area			2.65	0.35
BaEP	TC:917	Bark EP ∑ -> BaEP>1MW	0.93		0.93	
BaEP	TC:918	Bark EP ∑ -> BaEP<1MW	0.07		0.07	
FSWP	TC:915	Further sawnwood processing ∑ -> FPSWPC	0.90		0.90	
FSWP	TC:916	Further sawnwood processing ∑ -> ByPFWP	0.10		0.10	
FURA	TC:827	Fellings unrecorded assortments ∑ -> WFUn	0.47		0.47	
FURA	TC:828	Fellings unrecorded assortments ∑ -> SVLUn	0.25		0.25	
FURA	TC:829	Fellings unrecorded assortments ∑ -> Pun	0.28		0.28	
PP	TC:845	Plywood production ∑ -> ByPP	0.41		0.41	
PP	TC:846	Plywood production ∑ -> PWC	0.48		0.48	
PP	TC:902	Plywood production ∑ -> BaPP	0.00		0.11	
PuI	TC:851	Pulp industry ∑ -> PuP	0.94		0.94	
PuI	TC:852	Pulp industry ∑ -> BaPuI	0.06		0.06	
SI	TC:896	Sawmill Industry ∑ -> ByPSI	0.36		0.36	
SI	TC:897	Sawmill Industry ∑ -> SWP	0.54		0.54	
SI	TC:898	Sawmill Industry ∑ -> BaSI	0.10		0.10	
VP	TC:839	Veneer production ∑ -> ByPVP	0.42		0.42	
VP	TC:840	Veneer production ∑ -> VSC	0.47		0.47	
VP	TC:841	Veneer production ∑ -> BaVP	0.11		0.11	
	TS:0	∑ Transfer coefficients	0.00		0.00	
P0	BD:19	P0:Total stock delta			0.00	0.00
VI	BD:22	VI:Total stock delta			0.00	0.00
EPI	BD:36	EPI:Total stock delta			0.00	0.00
EP	BD:38	EP:Total stock delta			0.00	0.00
HAM	BD:63	HAM:Total stock delta			0.00	0.00
P0	BI:19	P0:Total input			29.05	0.59
VI	BI:22	VI:Total stock			0.32	0.07
EP	BI:36	EPI:Total input			0.70	0.02
EP	BI:38	EP:Total input			21.53	0.56
HAM	BI:63	HAM:Total input			22.90	0.48
P0	BO:19	P0:Total output			29.05	0.59
VI	BO:22	VI:Total stock			0.32	0.07
EPI	BO:36	EPI:Total output			0.70	0.02
EP	BO:38	EP:Total output			21.53	0.56
HAM	BO:63	HAM:Total output			22.90	0.48
VI	BS:31	VI:Total stock			0.00	0.00
P0	BS:38	P0:Total stock			0.00	0.00
EP	BS:51	EP:Total stock			0.00	0.00
EPI	BS:65	EPI:Total stock			0.00	0.00
HAM	BS:78	HAM:Total stock			0.00	0.00

Table S4. Reconciled Values with Standard Scores z in Comparison to Given and by MFA Calculated Values

		Standard scores z	Input flow value	Input standard uncertainty	Output flow value calculated	Output standard uncertainty calculated
PPP	Pulpwood for the pellet production	0.03	0.01	0	0.01	0
FPSWPC	Further processed sawnwood consumed	0.05	0.56	0.03	0.56	0.02
SWFSWP	Sawnwood for the further sawnwood processing	0.05	0.31	0.03	0.31	0.03
SWI	Sawnwood imported	0.08	0.32	0.05	0.32	0.03
BE	Briquettes exported	0.09	0	0	0	0
EPEP>1MW	Energy products for the EP > 1MW	0.09	0.01	0	0.01	0
WFEPI	Wood fuel for the energy product industry	0.35	0.06	0	0.06	0
PI	Pellet imported	0.35	0.07	0	0.07	0
ByPPP	By-products for the pellet production	0.56	0.3	0.02	0.29	0.01
EPEP<1MW	Energy products for the EP < 1 MW	0.61	0.08	0.01	0.09	0.01
BI	Briquettes imported	0.61	0.07	0.01	0.07	0.01
ByPBrP	By-products for the briquette production	0.78	0.04	0.02	0.02	0.02
Pex	Pellets exported	0.96	0.06	0.01	0.07	0.01
ByPEPI	By-products for the energy product industry	1.14	0.34	0.02	0.31	0.01
EPPEP	Energy products for the PEP	2.26	0.29	0.03	0.35	0.02

S5: 86 Equations

[1] FV:246 + FV:247 + FV:250 + FV:251 - FV:185 - FV:186 = 0

[2] FV:248 + FV:249 - FV:247 = 0

[3] FV:132 - FV:138 - FV:142 - FV:147 = 0

[4] FV:120 - FV:163 - FV:164 = 0

[5] FV:123 + FV:164 + FV:263 - FV:162 - FV:265 = 0

[6] FV:70 + FV:71 - FV:79 = 0

[7] FV:79 + FV:80 + FV:90 + FV:91 - FV:109 - FV:111 - FV:120 - FV:132 - FV:84 = 0

[8] FV:217 - FV:218 = 0

[9] FV:235 + FV:237 + FV:243 - FV:238 = 0

[10] BS:51 = 0

[11] BI:38 - FV:128 - FV:130 - FV:132 - FV:169 - FV:188 - FV:246 - FV:247 - FV:250 - FV:251 - FV:258 - FV:262 = 0

[12] BO:38 - FV:127 = 0

[13] BD:38 + BO:38 - BI:38 = 0

[14] FV:265 + FV:266 - FV:160 = 0

[15] FV:128 - FV:136 - FV:145 - FV:148 = 0

[16] BS:65 = 0

[17] BI:36 - FV:119 - FV:120 - FV:123 - FV:166 = 0

[18] BO:36 - FV:128 - FV:160 - FV:218 = 0

[19] BD:36 + BO:36 - BI:36 = 0

[20] FV:161 + FV:162 - FV:128 = 0

[21] FV:141 + FV:142 + FV:143 + FV:145 + FV:186 + FV:189 + FV:259 - FV:134 = 0

[22] FV:136 + FV:137 + FV:138 + FV:139 + FV:151 + FV:185 + FV:260 - FV:133 = 0

[23] FV:133 + FV:134 + FV:135 - FV:127 = 0

[24] FV:240 + FV:242 + FV:244 + FV:245 - FV:123 - FV:169 - FV:243 = 0

[25] FV:169 - FV:150 - FV:151 - FV:189 = 0

[26] FV:229 - FV:222 - FV:225 - FV:233 = 0

[27] FV:228 - FV:221 - FV:227 - FV:232 = 0

[28] FV:81 + FV:92 - FV:85 - FV:91 = 0

[29] FV:170 - FV:223 - FV:224 - FV:234 = 0

[30] FV:188 - FV:139 - FV:143 - FV:194 = 0

[31] BS:78 = 0

[32] BI:63 - FV:170 - FV:228 - FV:229 - FV:230 = 0

[33] BO:63 - FV:108 - FV:112 - FV:119 - FV:123 - FV:169 - FV:188 - FV:238 - FV:77 - FV:78 = 0

[34] BD:63 + BO:63 - BI:63 = 0

[35] FV:230 - FV:226 - FV:231 - FV:242 = 0

[36] FV:119 - FV:216 - FV:217 = 0

[37] FV:258 - FV:259 - FV:260 - FV:261 = 0

[38] FV:231 + FV:232 + FV:233 + FV:234 - FV:108 - FV:112 - FV:119 - FV:237 - FV:244 = 0

[39] BS:38 - BS:31 - BS:51 - BS:65 - BS:78 = 0

[40] BI:19 - FV:115 - FV:166 - FV:170 - FV:228 - FV:229 - FV:230 - FV:257 - FV:90 - FV:92 = 0

[41] BO:19 - FV:110 - FV:113 - FV:127 - FV:160 - FV:218 - FV:238 - FV:252 - FV:253 - FV:254 - FV:83 - FV:84 - FV:85 - FV:86 - FV:93 - FV:94 = 0

[42] BD:19 + BO:19 - BI:19 = 0

[43] FV:111 + FV:112 + FV:117 - FV:113 - FV:251 - FV:252 - FV:253 - FV:254 = 0

[44] FV:166 - FV:263 - FV:264 = 0

[45] FV:115 - FV:117 - FV:130 = 0

[46] FV:130 - FV:137 - FV:141 - FV:146 = 0

[47] FV:146 + FV:147 + FV:148 + FV:150 + FV:194 + FV:261 + FV:262 - FV:135 = 0

[48] FV:73 - FV:249 - FV:71 - FV:94 = 0

[49] FV:163 + FV:216 + FV:264 - FV:161 - FV:266 = 0

[50] FV:108 + FV:109 - FV:110 - FV:250 = 0

[51] FV:77 - FV:246 - FV:80 - FV:98 = 0

[52] FV:224 + FV:225 + FV:226 + FV:227 - FV:235 - FV:245 - FV:77 - FV:78 = 0

[53] FV:98 - FV:81 - FV:83 - FV:93 = 0

[54] BS:31 = 0

[55] BI:22 - FV:78 = 0

[56] BO:22 - FV:247 - FV:79 - FV:86 - FV:94 = 0

[57] BD:22 + BO:22 - BI:22 = 0

[58] FV:78 - FV:72 - FV:73 = 0

[59] FV:72 - FV:248 - FV:70 - FV:86 = 0

[60] FV:221 + FV:222 + FV:223 - FV:188 - FV:240 = 0

[61] FV:257 - FV:258 - FV:262 = 0

[62] FV:185 - TC:917 * FV:246 - TC:917 * FV:247 - TC:917 * FV:250 - TC:917 * FV:251 = 0

[63] FV:186 - TC:918 * FV:246 - TC:918 * FV:247 - TC:918 * FV:250 - TC:918 * FV:251 = 0

[64] TS:0 - TC:917 - TC:918 = 0

[65] FV:85 - TC:915 * FV:81 - TC:915 * FV:92 = 0

[66] FV:91 - TC:916 * FV:81 - TC:916 * FV:92 = 0

[67] TS:0 - TC:915 - TC:916 = 0

[68] FV:223 - TC:827 * FV:170 = 0

[69] FV:224 - TC:828 * FV:170 = 0

[70] FV:234 - TC:829 * FV:170 = 0

[71] TS:0 - TC:827 - TC:828 - TC:829 = 0

[72] FV:71 - TC:845 * FV:73 = 0

[73] FV:94 - TC:846 * FV:73 = 0

[74] FV:249 - TC:902 * FV:73 = 0

[75] TS:0 - TC:845 - TC:846 - TC:902 = 0

[76] FV:110 - TC:851 * FV:108 - TC:851 * FV:109 = 0

[77] FV:250 - TC:852 * FV:108 - TC:852 * FV:109 = 0

[78] TS:0 - TC:851 - TC:852 = 0

[79] FV:80 - TC:896 * FV:77 = 0

[80] FV:98 - TC:897 * FV:77 = 0

[81] FV:246 - TC:898 * FV:77 = 0

[82] TS:0 - TC:896 - TC:897 - TC:898 = 0

[83] FV:70 - TC:839 * FV:72 = 0

[84] FV:86 - TC:840 * FV:72 = 0

[85] FV:248 - TC:841 * FV:72 = 0

[86] TS:0 - TC:839 - TC:840 - TC:841 = 0

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