Supporting Information

Supplementary Note 1. Conventional machine learning framework for Li-ion battery SOH estimation

In this section, the working process of the conventional machine learning framework will be described in detail.

1.1 Data preprocessing and feature extraction

Battery degradation is a complex result of various mechanisms such as formation of the SEI layer and Li-plating. However, there are limitations to estimating battery health from the mechanisms because they occur inside the battery cell. Therefore, a phenomenological approach based on the features expressed in measurable parameters, such as voltage, capacity, and temperature, is required. Many researches have noted a pattern in cycling profiles with battery aging. For example, the initial voltage of discharge decreases and the peak of the charge IC curve shifts as cycling progresses, as shown in **Supplementary Fig. S4-S6**. Therefore, to analyze D-GELS performance comparatively, we analyzed the salient patterns of profiles. 35 features were extracted as battery health indicators to construct conventional frameworks (**Supplementary Table 2**). The 35 features are categorized into three groups, voltage-related features, cell surface temperature-related features, and incremental capacity-related features. Some of the extracted features are closely related to battery aging, but there will also be features that have no relation or are negligible. They not only increase computational cost but can also cause overfitting problems. Therefore, the process of selecting the optimal feature set is necessary.

1.2 Feature selection

In this paper, four feature selection strategies are concerned: Filter method, Feature Selector, PCA, and ElasticNet (**Supplementary Table 3**). Firstly, the filter method was set the threshold as 0.05 to remove quasi-constant features with *VarianceThreshold()* function in *sklearn.feature_selection*, and the Pearson correlation as 0.7 to remove correlated features with *corr()* function in *Pandas*. The remained 10 features were selected. The Feature Selector was set the parameters 'missing_threshold' as '0.6', 'correlation_threshold' as '0.98', 'task' as 'regression', 'eval_metric' as 'auc', and 'cumulative_importance' as '0.98'. The remaining 7 features were selected. In the PCA method, the feature eigenvalues were sorted and top 8 features were selected because the cumulated explained variance ratio is over 0.9 after the 8th eigenvalue. The PCA was processed with *PCA* library of *sklearn.decomposition.* Finally, the ElasticNet was set the parameters 'alpha' as '0.3' with the optimizing process using *ElasticNetCV()* in *sklearn.linear_model*. And 6 features were selected.

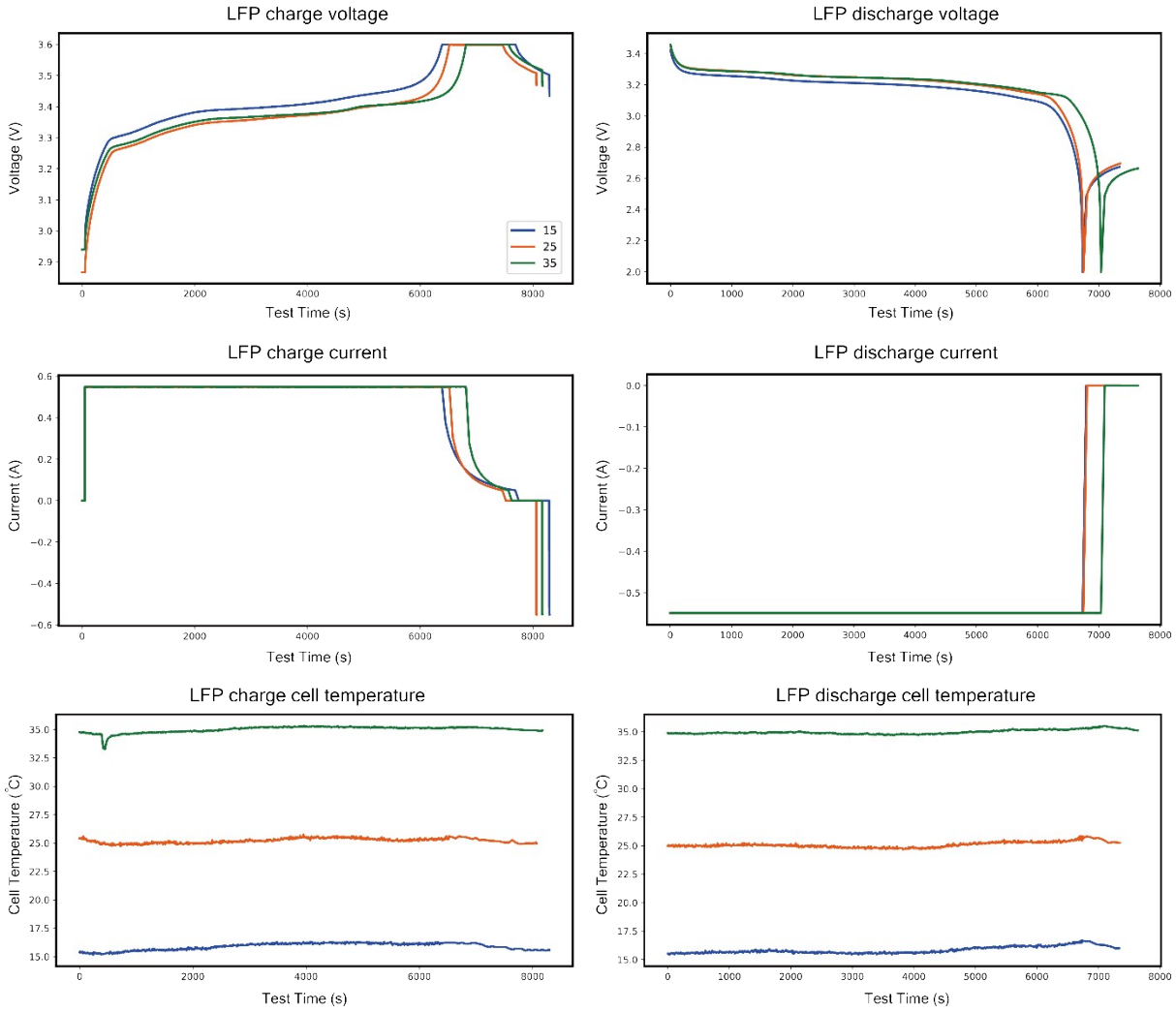
The K-Nearest Neighbor (KNN) model is used as the basic SOH prediction model to find out the optimal feature set. The parameter was set 'n_neighbors' as '5', 'metric' as 'minkowski', and 'weights' as 'uniform' (**Supplementary Table 3**). As a result, the feature set which was selected by the Feature selector has the best performance, 0.005196 of RMSE.

1.3 Compared SOH estimation performance with D-GELS

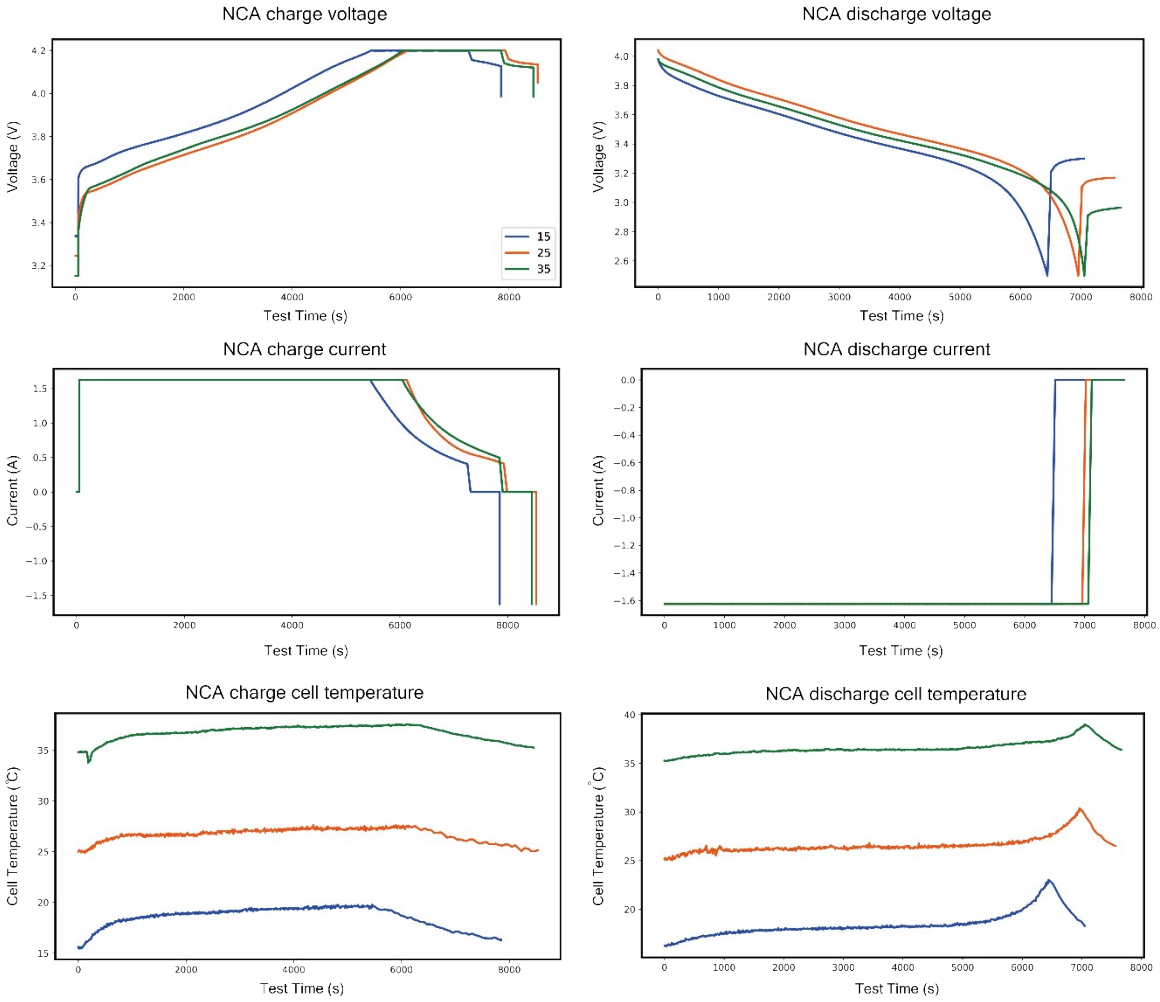
In this section, the 7 feature set which was selected with Feature Selector was fed into four machine learning models to estimate SOH: GPR, SGD, RF, NuSVR. The GPR are set 'alpah' as '0.01' with *GaussianProcessRegressor()* in *sklearn.gaussian_process*. The SGD are set with default parameters with *SGDClassifier()* in *sklearn.linear_model*. The RF was set 'max_depth'

as ‘10’, ‘random_state’ = ‘0’ with *RandomForestRegressor()* in *sklearn.ensemble*. And the NuSVR are set ‘kernel’ as ‘linear’, ‘C’ as ‘1.0’, ‘gamma’ as ‘auto’.

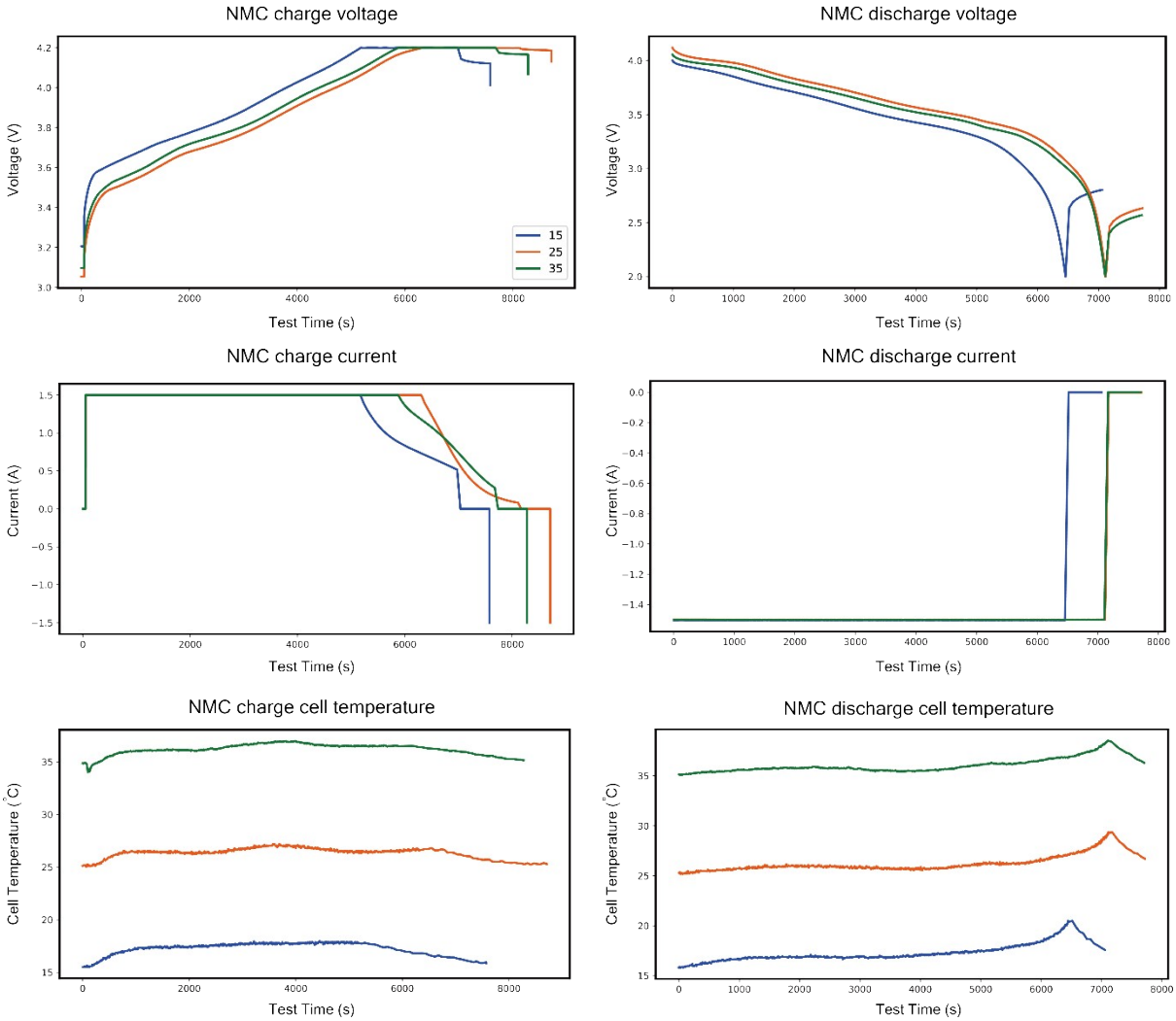
After the models were trained, performance degradation was compared with D-GELS when the training dataset (25℃) and the test dataset (15℃ and 35℃) have different cycling temperature conditions (**Supplementary Table 4**).



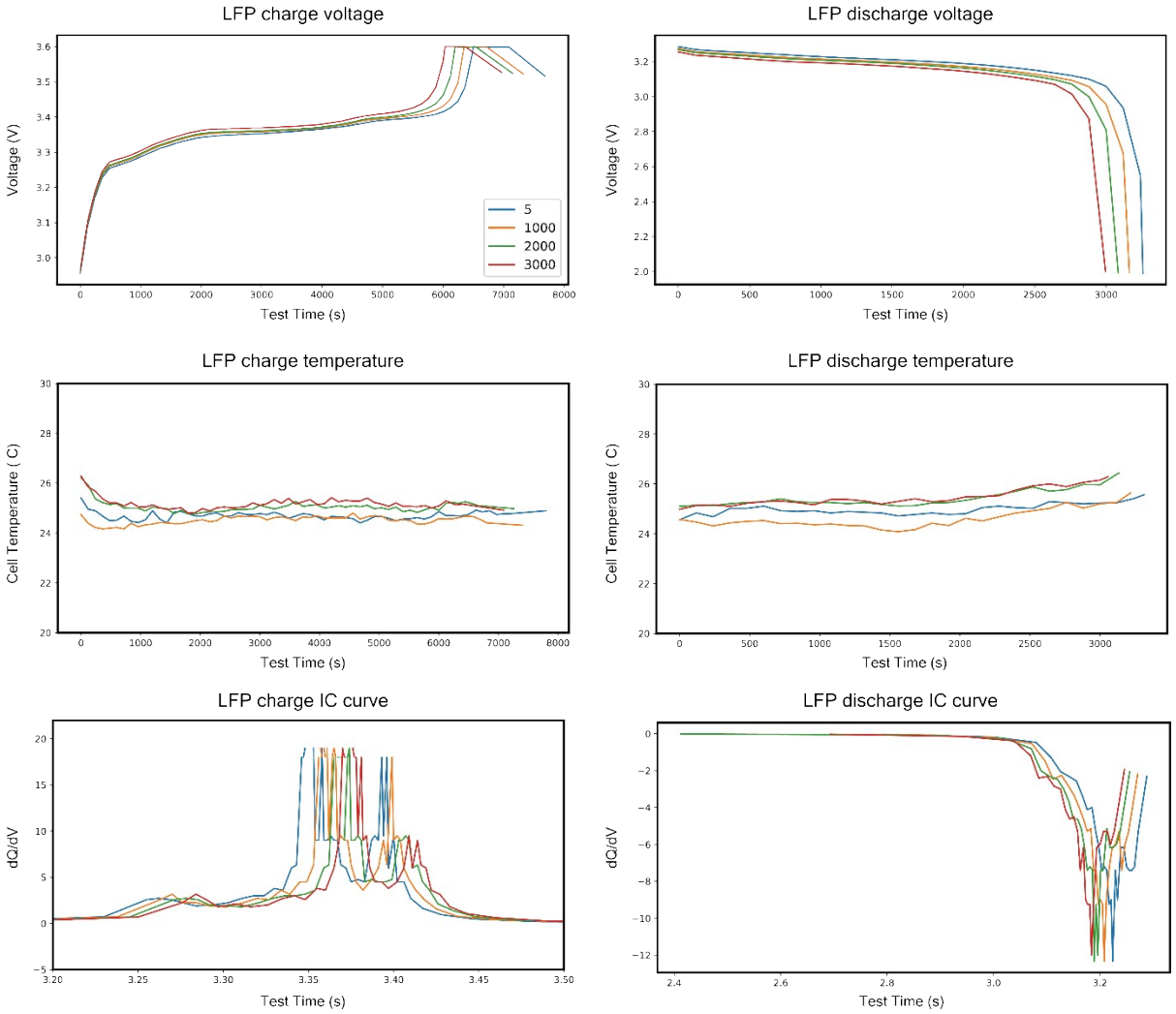
Supplementary Fig. 1. The initial cycling curves of a battery with LFP cathode material cycled at environmental temperatures of 15℃, 25℃, and 35℃. The voltage, current, and cell temperature profiles at 25℃ were used for D-GELS training, and the cycling data at 15℃ and 35℃ were used for applicability evaluation.



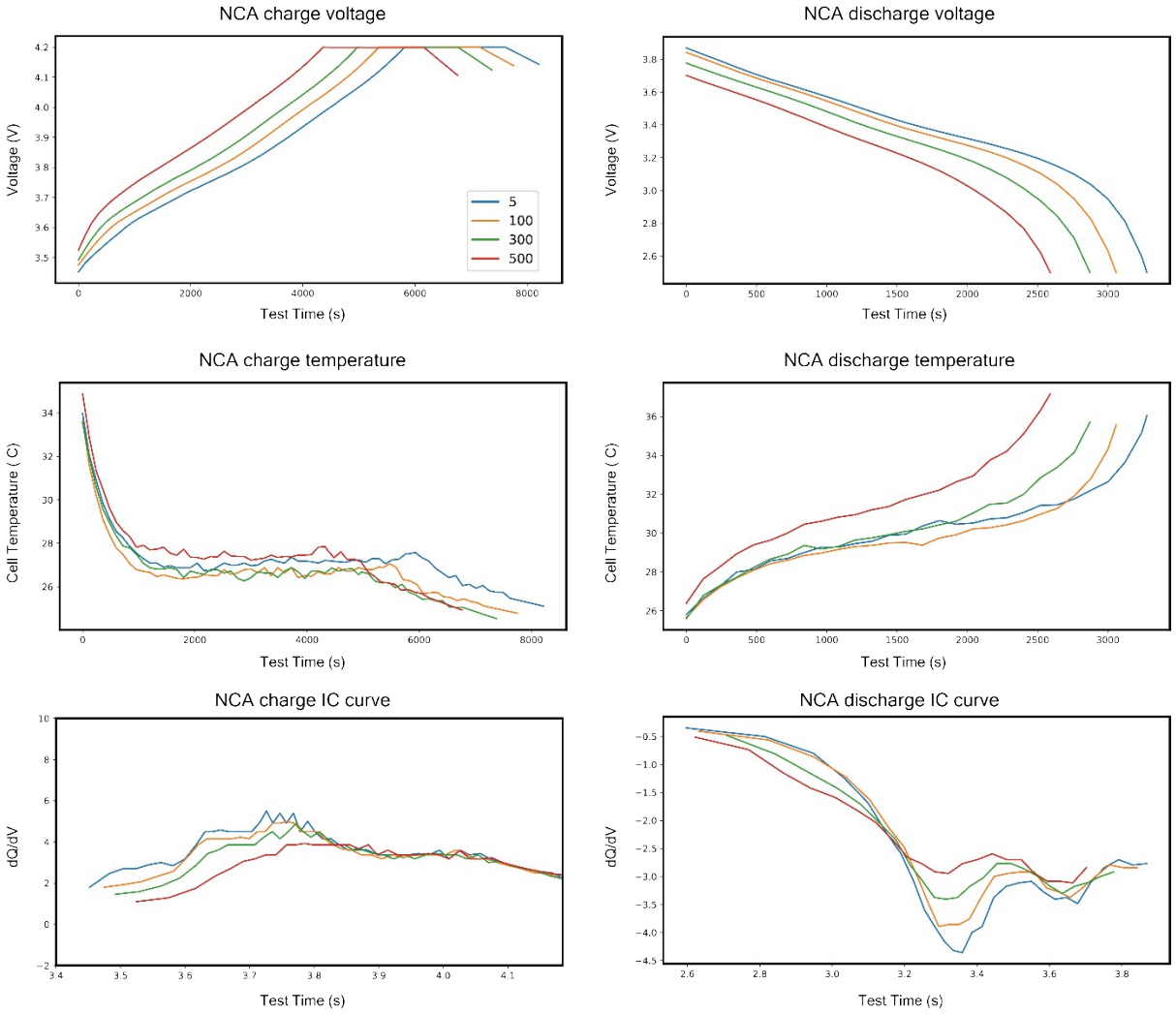
Supplementary Fig. 2. The initial cycling curves of a battery with NCA cathode material cycled at environmental temperatures of 15℃, 25℃, and 35℃. The voltage, current, and cell temperature profiles at 25℃ were used for D-GELS training, and the cycling data at 15℃ and 35℃ were used for applicability evaluation.



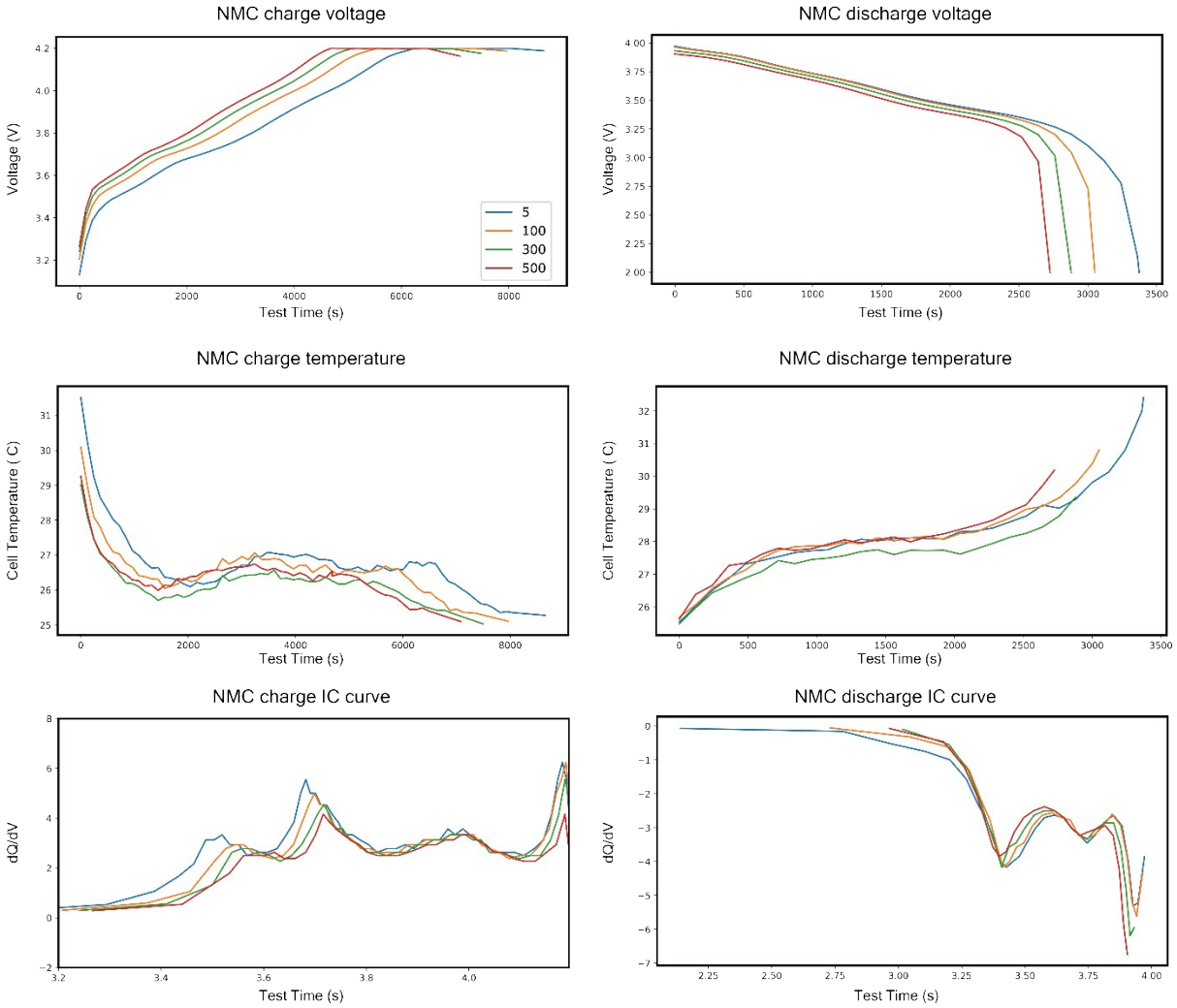
Supplementary Fig. 3. The initial cycling curves of a battery with NMC cathode material cycled at environmental temperatures of 15℃, 25℃, and 35℃. The voltage, current, and cell temperature profiles at 25℃ were used for D-GELS training, and the cycling data at 15℃ and 35℃ were used for applicability evaluation.



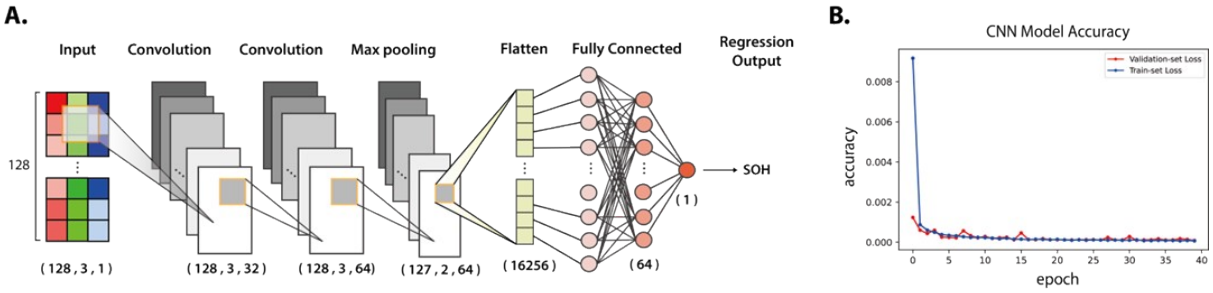
Supplementary Fig. 4. The voltage, cell temperature, and IC curves of battery cycling with LFP cathodes at 5, 1000, 2000, and 3000 cycles.



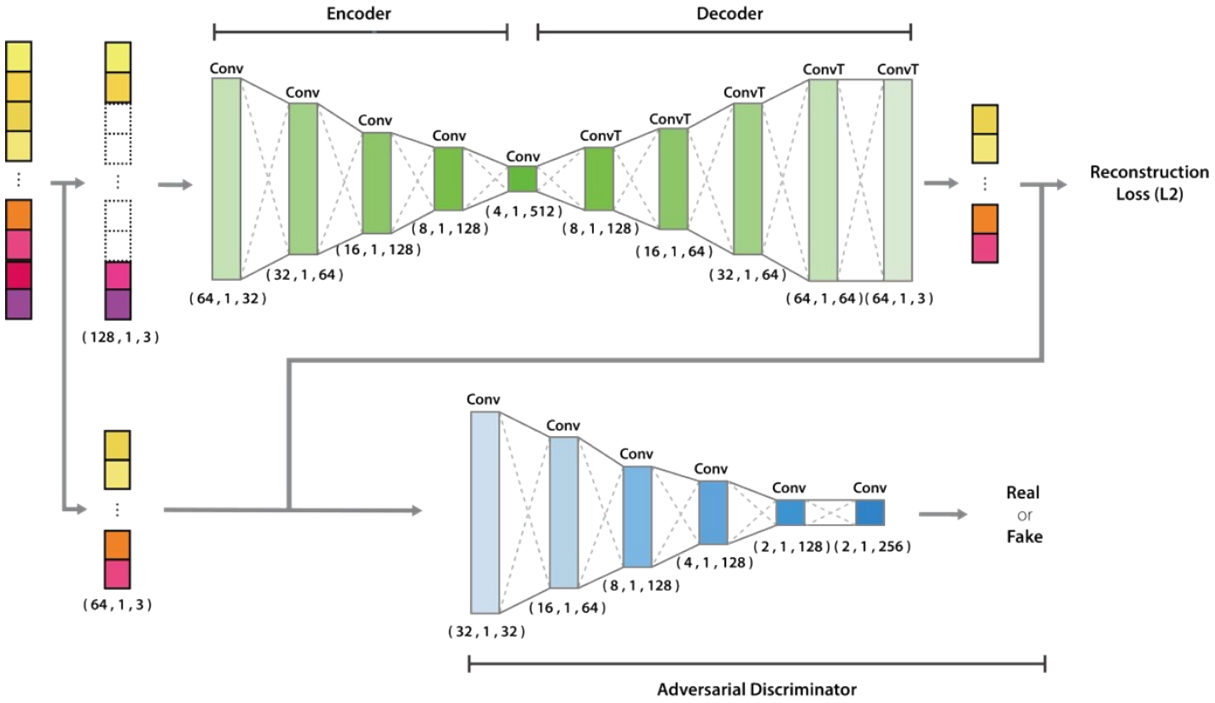
Supplementary Fig. 5. The voltage, cell temperature, and IC curves of battery cycling with NCA cathodes at 5, 100, 300, and 500 cycles.



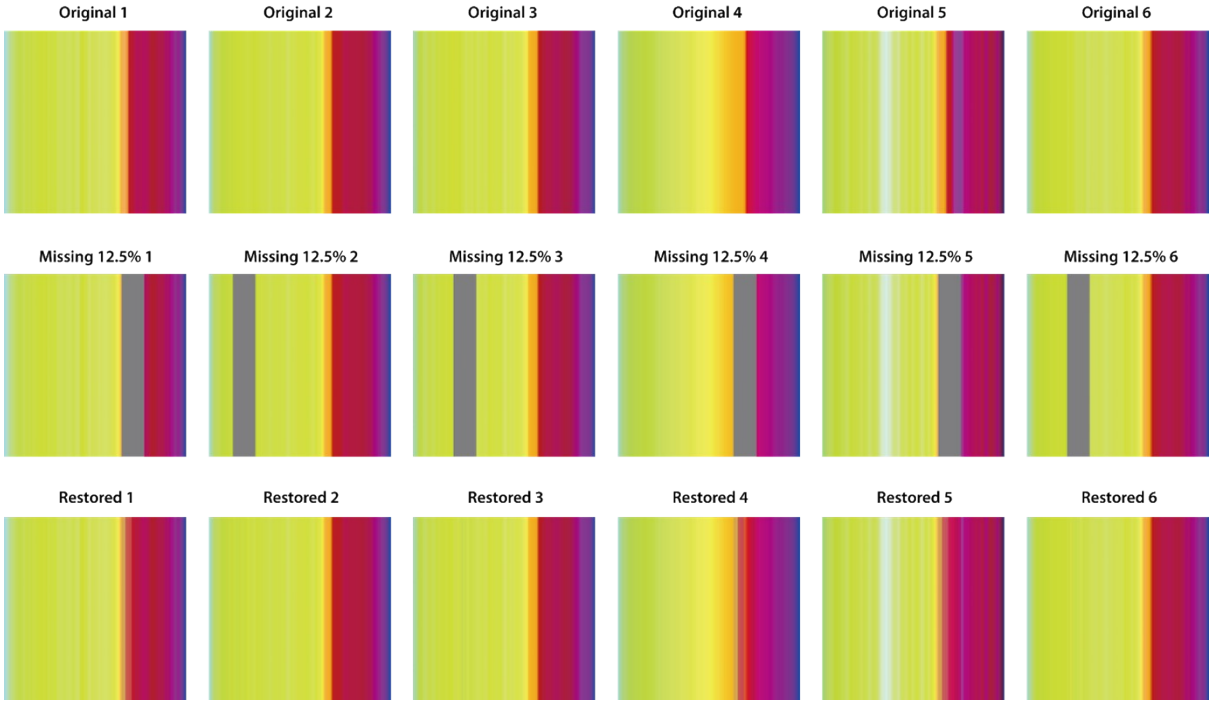
Supplementary Fig. 6. The voltage, cell temperature, and IC curves of battery cycling with NMC cathodes at 5, 100, 300, and 500 cycles.



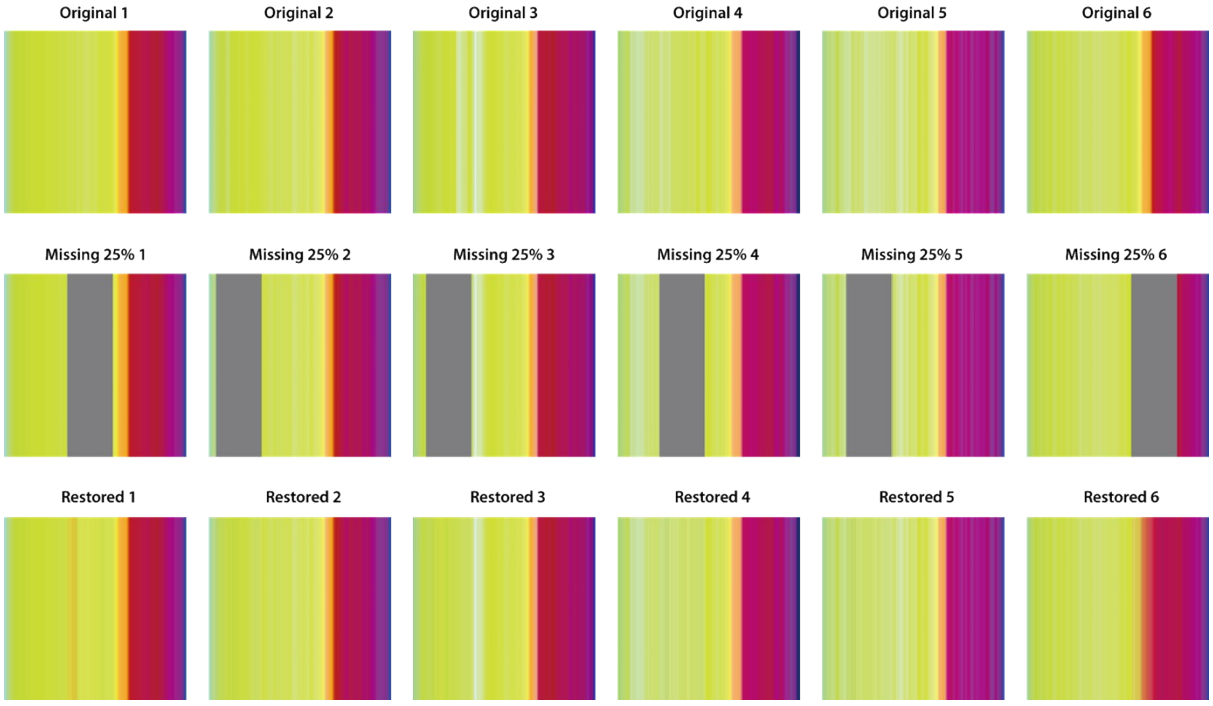
Supplementary Fig. 7. (A) The Convolutional Neural Network architecture for SOH estimation. (B) Training and validation loss over epochs obtained by training the CNN regression model.



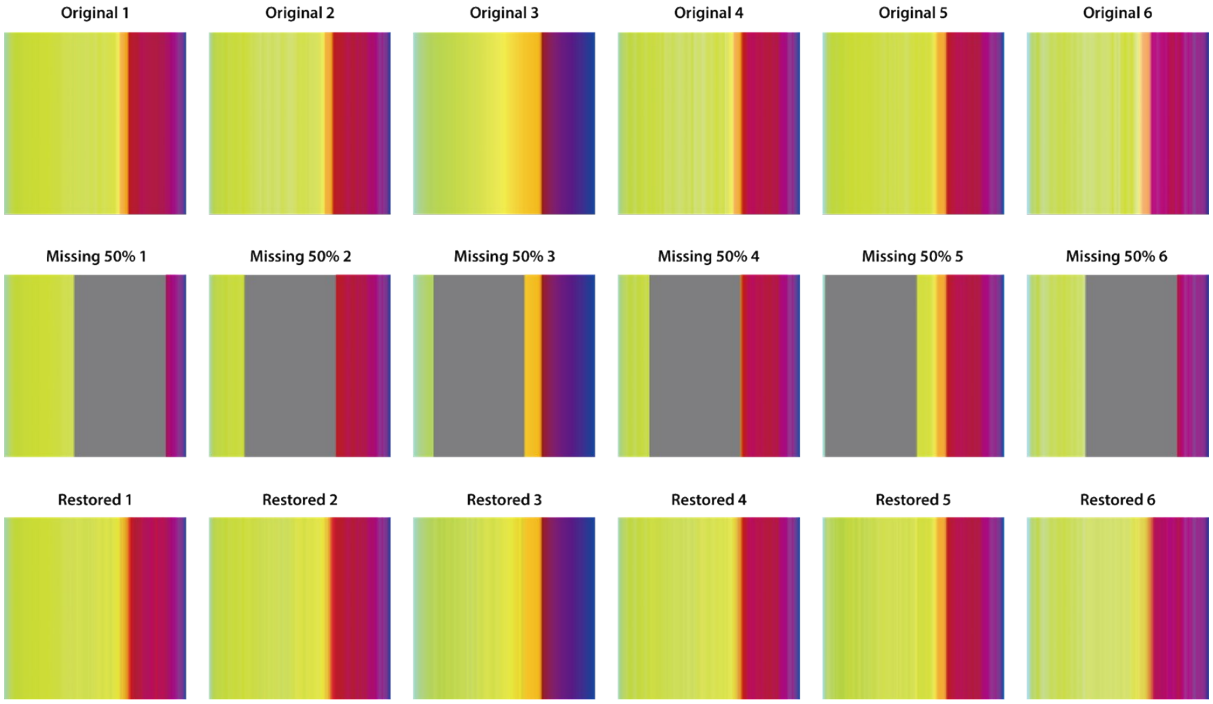
Supplementary Fig. 8. The Context Encoders architecture for restored inpainting V, I, T - spatial channels in which the missing part accounts for 50% of the original.



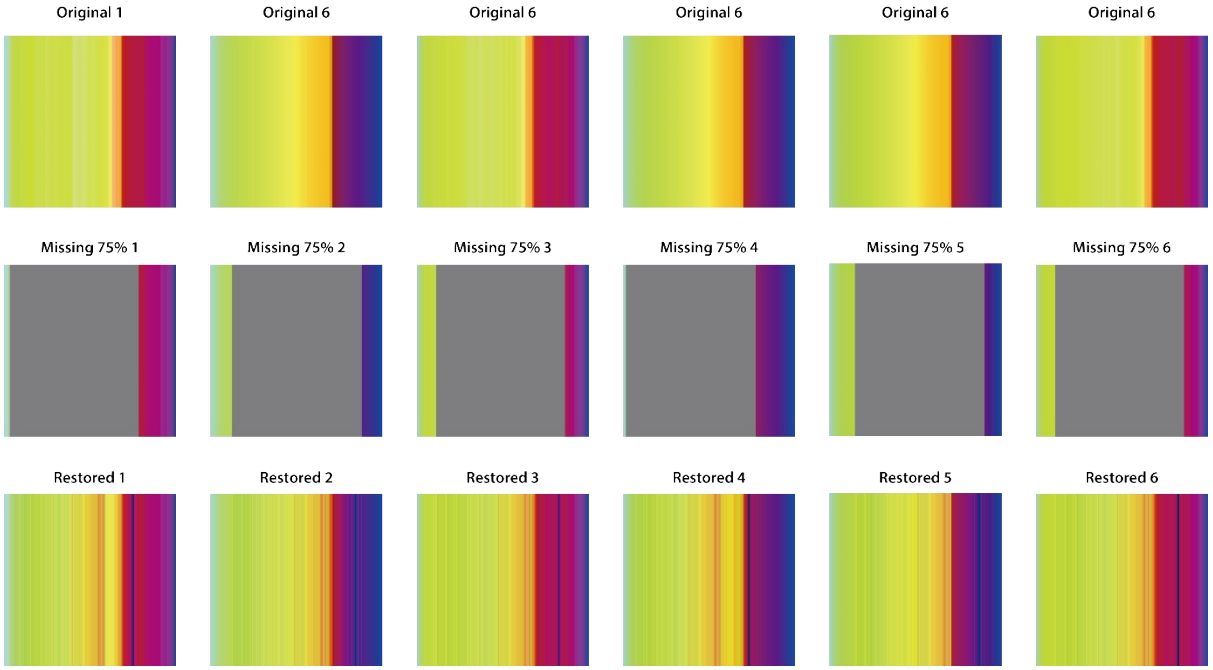
Supplementary Fig. 9. Examples of restored 12.5% missing spatio-temporal channels by D-GELS.



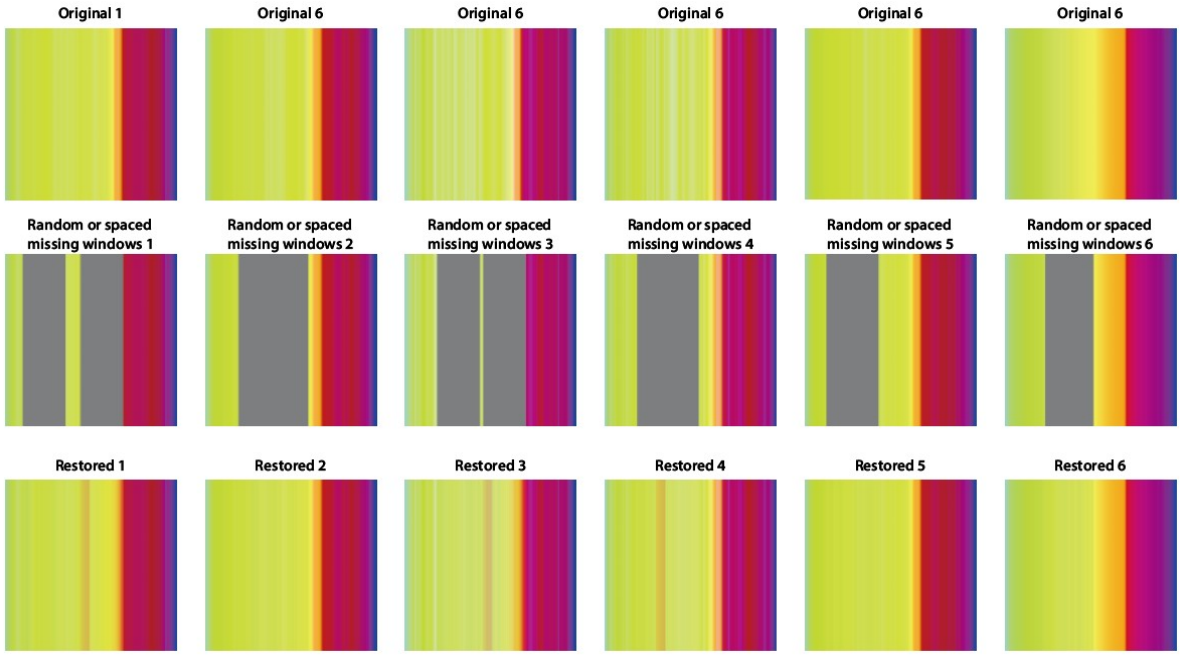
Supplementary Fig. 10. Examples of restored 25% missing spatio-temporal channels by D-GELS.



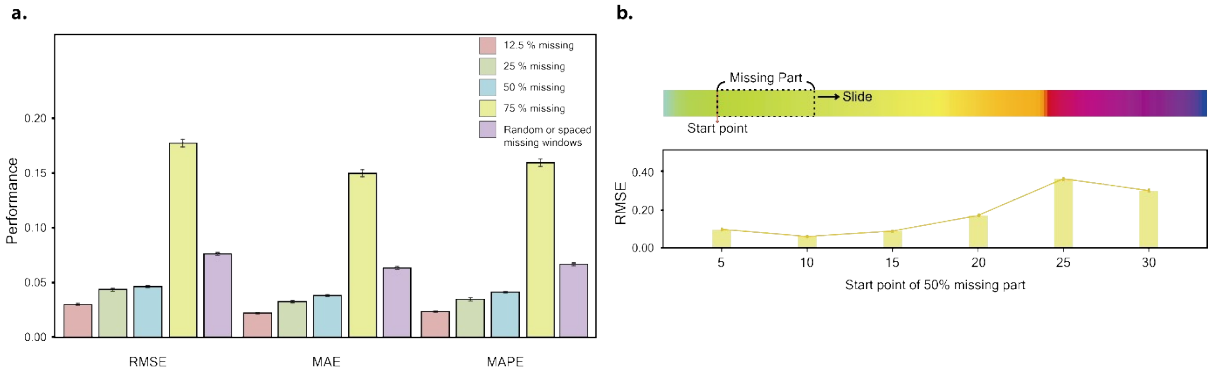
Supplementary Fig. 11. Examples of restored 50% missing spatio-temporal channels by D-GELS.



Supplementary Fig. 12. Examples of restored 75% missing spatio-temporal channels by D-GELS.



Supplementary Fig. 13. Examples of restored random size of the missing window between 25% and 50% or two 25% missing windows randomly spaced.



Supplementary Fig. 14. The performance of D-GELS in SOH estimation with the restored partial-cycling profiles. (a) The performance of D-GELS in predicting SOH with partial-cycling data of 12.5%, 25%, 50% or 75% missing, or random or spaced missing windows in terms of three error metrics: RMSE, MAE, and MAPE. (b) RMSE according to the initial position of the 75% missing part as the missing window is moved across the spatio-temporal channel from start to end.

	D-GELS			LFP			NCA			NMC		
	RMSE	MAE	MAPE	RMSE	MAE	MAPE	RMSE	MAE	MAPE	RMSE	MAE	MAPE
Try 1	0.010603	0.008417	0.009191	0.00906	0.00726	0.007585	0.014266	0.012283	0.014535	0.014182	0.011325	0.013261
Try 2	0.008556	0.005599	0.006066	0.008166	0.00536	0.005606	0.008209	0.005978	0.007121	0.011019	0.006735	0.007913
Try 3	0.008075	0.006386	0.006942	0.007479	0.006003	0.006277	0.011625	0.009689	0.011558	0.007176	0.005416	0.006353
Try 4	0.009171	0.006931	0.007639	0.007388	0.005872	0.006124	0.01597	0.012922	0.015836	0.008915	0.00693	0.008075
Try 5	0.007127	0.00535	0.005789	0.006483	0.004944	0.005153	0.009891	0.007586	0.008977	0.007599	0.005622	0.00651
Try 6	0.008786	0.006896	0.007522	0.007861	0.006217	0.006502	0.011218	0.008809	0.010513	0.011136	0.009221	0.010889
Try 7	0.007975	0.005995	0.0065	0.007569	0.005857	0.006129	0.009368	0.00679	0.008114	0.008838	0.006024	0.00714
Try 8	0.00859	0.006429	0.00692	0.008077	0.006174	0.006415	0.010524	0.007645	0.008955	0.009512	0.00682	0.008044
Try 9	0.010505	0.007578	0.008208	0.010592	0.007471	0.007846	0.012095	0.009661	0.011367	0.008003	0.00617	0.007268
Try 10	0.009074	0.006766	0.00734	0.008186	0.006287	0.00655	0.011861	0.009347	0.011364	0.010691	0.006849	0.007764

Supplementary Table 1. The SOH estimation performance of D-GELS, and SOH estimation performance according to cathode materials of 10 iterations.

Feature Type	State	No.	Description
Voltage related features	Charge	F1	Initial voltage value
		F2	Area of voltage profile
		F3	Final voltage value
		F4	Time at which the last voltage was measured
		F5	Area of 15 points in front
		F6	Slope of 15 points in front
		F7	Skewness of 15 points in front
		F8	Kurtosis of 15 points in front
	Discharge	F9	Initial voltage value
		F10	Area of voltage profile
		F11	Final voltage value
		F12	Time at which the last voltage was measured
		F13	Area of 15 points behind
		F14	Slope of 15 points behind
		F15	Skewness of 15 points behind
		F16	Kurtosis of 15 points behind
Temperature related features	Charge	F17	Initial temperature value
		F18	Area of temperature profile
		F19	Slope of temeperature profile
		F20	Final temperature value
		F21	Area of initial 15 points in front
		F22	Slope of initial 15 points in front
		F23	Skewness of initial 15 points in front
		F24	Kurtosis of initial 15 points in front
	Discharge	F25	Area of temperature profile
		F26	Slope of temeperature profile
		F27	Area of initial 15 points in front
		F28	Slope of initial 15 points in front
		F29	Skewness of initial 15 points in front
		F30	Kurtosis of initial 15 points in front
		F31	Final temperature value
IC related features	Charge	F32	Global peak value of IC curve
		F33	Time at which the global peak was measured
		F34	Local peak value of IC curve
		F35	Time at which the local peak was measured

Supplementary Table 2. The extracted features for the traditional method of SOH prediction.

		Before Selection (35)	Filter Method (10)	Feature Selector (7)	PCA (8)	ElasticNet (6)
Selected Features		F1 - F35	F2, F4, F7, F12, F23, F24, F29, F30, F33, F34	F4, F6, F12, F14, F15, F18, F35	F4, F6, F20, F23, F24, F29, F30, F35	F2, F4, F12, F25, F33, F35
KNN Performance	RMSE	0.008107	0.009912	0.005196	0.015226	0.005321
	MAE	0.005011	0.007167	0.001829	0.008614	0.002196
	MAPE	0.005408	0.007688	0.002054	0.009360	0.002471

Supplementary Table 3. The selected features with Filter Method, Feature Selector, PCA, and ElasticNet, and the SOH estimation performance of KNN. The number of selected features is written in brackets and the feature list is shown in the Supplementary Table 2.

label	data	rmse	mse	mae	mape
GPR	tot	0.006857	4.70E-05	0.005011	0.005435
	15C	0.251524	0.063265	0.237577	0.259436
	35C	0.135292	0.018304	0.128125	0.142125
SGD	tot	0.022219	0.000494	0.01622	0.0179
	15C	0.143255	0.020522	0.136567	0.148579
	35C	0.129893	0.016872	0.128152	0.14145
RF	tot	0.007298	5.33E-05	0.004515	0.00489
	15C	0.045599	0.002079	0.040085	0.042773
	35C	0.081192	0.006592	0.071445	0.077452
NuSVR	tot	0.013635	0.000186	0.008818	0.009679
	15C	0.167027	0.027898	0.137356	0.153879
	35C	0.181844	0.033067	0.179002	0.19887
D-GELS	tot	0.008846	7.93E-05	0.006634	0.007211
	15C	0.031466	0.000990	0.019413	0.020985
	35C	0.030541	0.000933	0.028264	0.031409

Supplementary Table 4. The SOH estimation performance of GPR, SGD, RF, and NuSVR with selected features, and D-GELS.

	RMSE					MAE					MAPE				
	12.5%	25%	50%	75%	random	12.5%	25%	50%	75%	random	12.5%	25%	50%	75%	random
Try 1	0.030349	0.039853	0.046976	0.182831	0.076835	0.021731	0.028682	0.038925	0.159354	0.062298	0.023185	0.030497	0.041977	0.169591	0.066133
Try 2	0.028050	0.042943	0.042886	0.176285	0.075828	0.022009	0.032017	0.034929	0.151094	0.062372	0.023434	0.034222	0.037988	0.16154	0.066288
Try 3	0.029138	0.044936	0.047358	0.167782	0.079222	0.022036	0.034404	0.038160	0.139189	0.064131	0.023757	0.036924	0.041407	0.148842	0.067716
Try 4	0.027773	0.044853	0.047227	0.185845	0.076663	0.022412	0.033397	0.038699	0.153477	0.063289	0.023951	0.035605	0.041869	0.163555	0.067439
Try 5	0.030632	0.039372	0.046397	0.179705	0.07844	0.022470	0.030238	0.037553	0.152245	0.061866	0.024405	0.032170	0.040104	0.160857	0.065608
Try 6	0.031811	0.045224	0.047805	0.176973	0.079562	0.022720	0.034574	0.039529	0.14845	0.066759	0.024628	0.036743	0.042535	0.160367	0.071291
Try 7	0.030236	0.044592	0.047350	0.17531	0.079142	0.021692	0.029779	0.040024	0.148498	0.065507	0.023403	0.031959	0.043095	0.156458	0.070439
Try 8	0.031689	0.044793	0.047674	0.167983	0.072641	0.022821	0.034567	0.039606	0.1436	0.060136	0.024251	0.036972	0.042327	0.153418	0.063954
Try 9	0.027439	0.045471	0.046517	0.184385	0.07444	0.019735	0.035234	0.038822	0.153024	0.061366	0.020936	0.037570	0.041737	0.161211	0.065252
Try 10	0.032601	0.045696	0.044751	0.178507	0.075252	0.023518	0.033826	0.036603	0.149516	0.06225	0.025203	0.036023	0.040219	0.159178	0.06616

Supplementary Table 5. The SOH estimation performance of D-GELS with restored 12.5%, 25%, 50%, or 75%, or random or spaced missing windows.

	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105
Try 1	0.019317	0.018602	0.020862	0.010077	0.012148	0.011513	0.029388	0.02455	0.019365	0.023106	0.033377	0.040702	0.126208	0.062993	0.019894	0.018129	0.026601	0.008566	0.018753	0.011135	0.032126
Try 2	0.019178	0.01878	0.020635	0.009981	0.012282	0.011596	0.02923	0.024329	0.019698	0.02286	0.034133	0.042278	0.126004	0.062227	0.020052	0.016762	0.026008	0.008603	0.019459	0.011499	0.032796
Try 3	0.018194	0.018618	0.019327	0.01097	0.012502	0.011514	0.029897	0.023983	0.019548	0.02328	0.034471	0.042038	0.124161	0.061874	0.020392	0.01819	0.027624	0.008562	0.019152	0.011784	0.032043
Try 4	0.017944	0.018575	0.019994	0.010998	0.012255	0.011524	0.029835	0.024406	0.018881	0.022518	0.03419	0.040627	0.124717	0.063581	0.02058	0.018182	0.026923	0.009019	0.01936	0.011648	0.032114
Try 5	0.019115	0.017906	0.020685	0.009457	0.012365	0.011424	0.030159	0.023855	0.019807	0.022032	0.033729	0.041978	0.125596	0.062854	0.018917	0.016651	0.028097	0.008861	0.017651	0.011889	0.032606
Try 6	0.019034	0.018664	0.020566	0.010782	0.011669	0.011374	0.029697	0.02428	0.019984	0.022863	0.033328	0.041993	0.126003	0.06179	0.019501	0.018219	0.027461	0.008286	0.019127	0.011905	0.032559
Try 7	0.019118	0.019206	0.02089	0.009916	0.012091	0.011695	0.028924	0.023672	0.019985	0.023229	0.034046	0.042334	0.122947	0.063528	0.019898	0.017849	0.027567	0.008892	0.01795	0.010601	0.032111
Try 8	0.019139	0.018926	0.019964	0.010845	0.012734	0.011037	0.028788	0.0244	0.019689	0.023272	0.033588	0.041998	0.124236	0.06296	0.020411	0.01715	0.026081	0.008098	0.018638	0.01198	0.032342
Try 9	0.019116	0.019031	0.020456	0.009923	0.011684	0.011243	0.030055	0.024384	0.019832	0.022062	0.034403	0.040404	0.125697	0.062302	0.020158	0.018092	0.027974	0.008668	0.019518	0.01052	0.033048
Try 10	0.018703	0.018392	0.019755	0.01034	0.011633	0.011726	0.02971	0.02363	0.0197	0.021511	0.033775	0.042444	0.123539	0.063769	0.019705	0.018155	0.026576	0.009054	0.018699	0.010308	0.031712

Supplementary Table 6. The results of D-GELS according to starting position of the 12.5% missing part.

	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
Try 1	0.014342	0.014058	0.012064	0.011809	0.009857	0.016	0.047665	0.046779	0.042195	0.053697	0.06418	0.07872	0.117032	0.01998	0.019592	0.066447	0.082157	0.012747
Try 2	0.013646	0.014287	0.011458	0.012371	0.010675	0.016547	0.047626	0.0469	0.040344	0.053558	0.060647	0.078092	0.117056	0.020824	0.021074	0.065278	0.081317	0.013457
Try 3	0.015086	0.01396	0.01225	0.012827	0.00975	0.016721	0.047057	0.045667	0.042324	0.052246	0.064213	0.079378	0.119007	0.021321	0.019218	0.066425	0.08105	0.012315
Try 4	0.013972	0.014252	0.012707	0.012178	0.010981	0.016627	0.047482	0.044087	0.04196	0.053281	0.065045	0.079199	0.116974	0.019615	0.02164	0.065998	0.077932	0.014448
Try 5	0.015583	0.014311	0.012594	0.011501	0.010389	0.015558	0.047537	0.044633	0.039149	0.053342	0.064343	0.079679	0.117496	0.021258	0.021699	0.066709	0.081769	0.014298
Try 6	0.015478	0.013921	0.012636	0.012439	0.009879	0.016525	0.047614	0.045675	0.042406	0.05198	0.064447	0.077992	0.118539	0.020105	0.0217	0.065845	0.081059	0.013681
Try 7	0.015244	0.013247	0.01184	0.012078	0.011088	0.015933	0.046684	0.046788	0.041566	0.053362	0.058602	0.07791	0.114578	0.020637	0.021923	0.064364	0.080375	0.014473
Try 8	0.015108	0.013437	0.012126	0.012116	0.009751	0.015967	0.046429	0.045937	0.042003	0.052698	0.063517	0.07872	0.119703	0.019066	0.020324	0.065274	0.081535	0.013507
Try 9	0.014175	0.01444	0.012528	0.01286	0.010988	0.016387	0.047425	0.047038	0.041972	0.052868	0.064609	0.079198	0.119821	0.019697	0.021529	0.066557	0.081029	0.013713
Try 10	0.014459	0.013798	0.011546	0.012472	0.010541	0.016809	0.047793	0.046746	0.041566	0.052763	0.062398	0.07876	0.117336	0.020699	0.021449	0.063379	0.081495	0.014875

Supplementary Table 7. The results of D-GELS according to starting position of the 25% missing part.

	5	10	15	20	25	30	35	40	45	50	55
Try 1	0.01783	0.017142	0.020867	0.043507	0.072168	0.046794	0.049099	0.066564	0.058449	0.040213	0.052551
Try 2	0.017262	0.017208	0.023876	0.042145	0.071398	0.047629	0.049309	0.067232	0.058861	0.041836	0.051638
Try 3	0.017961	0.0165	0.022536	0.041123	0.071022	0.047001	0.04557	0.066185	0.058734	0.04161	0.049836
Try 4	0.017683	0.01747	0.021793	0.042934	0.070789	0.049515	0.047629	0.065631	0.059044	0.040728	0.050389
Try 5	0.017908	0.016601	0.023755	0.042777	0.069093	0.048835	0.048476	0.066659	0.058571	0.040493	0.052411
Try 6	0.018242	0.017502	0.025122	0.042878	0.070705	0.049305	0.049463	0.065693	0.056409	0.04111	0.052354
Try 7	0.017847	0.017733	0.023597	0.042708	0.072114	0.047754	0.048373	0.064791	0.059262	0.040468	0.052362
Try 8	0.017526	0.015007	0.024769	0.043463	0.071473	0.050032	0.048786	0.066679	0.060043	0.04005	0.053219
Try 9	0.01804	0.015817	0.026176	0.042312	0.070456	0.049657	0.047594	0.065652	0.058769	0.041491	0.051643
Try 10	0.017789	0.017663	0.026085	0.042227	0.070092	0.049301	0.048095	0.066077	0.059353	0.039745	0.051413

Supplementary Table 8. The results of D-GELS according to starting position of the 50% missing part.

	5	10	15	20	25	30
Try 1	0.099485	0.060432	0.090815	0.172597	0.363521	0.301648
Try 2	0.099768	0.061444	0.093085	0.173174	0.360603	0.294038
Try 3	0.10092	0.065614	0.086964	0.171891	0.362239	0.29829
Try 4	0.10251	0.065594	0.092086	0.172808	0.36303	0.301753
Try 5	0.10132	0.06427	0.093254	0.169041	0.359488	0.301406
Try 6	0.101758	0.064309	0.092779	0.171545	0.36189	0.300778
Try 7	0.099287	0.063092	0.093614	0.17169	0.361841	0.300873
Try 8	0.102382	0.064656	0.092274	0.173279	0.360915	0.299602
Try 9	0.101485	0.06542	0.092924	0.170282	0.356515	0.3017
Try 10	0.101209	0.064232	0.093593	0.172862	0.360589	0.299104

Supplementary Table 9. The results of D-GELS according to starting position of the 75% missing part.

		Time (minute)	Cost (€)
Inspection and handling		60	100
Connection of the electrical test equipment		10	17
Initial voltage set and balance		100	83
Battery characterization		-	208
Disconnection from electrical test equipment		10	17
Final inspection		10	17
LFP	50%	82.02	-
	75%	124.03	-
	100%	183.35	-
NCA	50%	62.02	-
	75%	94.02	-
	100%	149.95	-
NMC	50%	56.02	-
	75%	86.02	-
	100%	139.20	-

Supplementary Table 10. Economic and technical parameters.